NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

June 8, 2022

POWERPLANT GROUP CHAIRMAN'S FACTUAL REPORT

NTSB No. ENG18IA003

A. ACCIDENT

Location: Seattle, Washington

Date: November 7, 2017

Time: Approximately 2102 Pacific Daylight Time

Aircraft: Airbus A330-200, Registration N375HA

Operator: Hawaiian Airlines

B. POWERPLANTS GROUP

Powerplant Group Chairman:
Harald Reichel
National Transportation Safety Board
Washington, DC

Member:
Mark Brock
Federal Aviation Administration
Dallas, Texas

Member:
Bennett Walsh
Hawaiian Airlines
Honolulu, Hawaii

Member:
Mark Walker
Rolls Royce
Derby, England

Member:
Stuart Hawkins
Air Accidents Investigation Branch
Hampshire, United Kingdom

C. SUMMARY

On November 7, 2017 at approximately 9:00 PM Pacific Daylight Time a Hawaiian Airlines Airbus A330-243 airplane, Registration Number N375HA, flight 8075, sustained a control issue of the left-hand (LH) Rolls Royce (R-R) Trent 700 turbofan engine resulting in pulses of flame from the aft of the engine just after landing on runway16L at Seattle-Tacoma International Airport (SEA). After touchdown, the engine emitted sufficient liquid fuel and flames from the exhaust to cause thermal damage to the nacelle, pylon, wing, and flaps. The repositioning flight originated at Paine Field (PAE), Washington and was on a ferry flight after having interior upgrades installed, a 10-day job, and was enroute to Seattle, Washington, to begin regular service. No engine work was carried out during this period.

There were two crew and no passengers on board. It was reported that the pilot was unaware of the fire and was informed of the condition by the control tower. The first officer shut down the left engine using the engine fire switch and discharged one fire bottle. Seattle aircraft rescue and Firefighting (ARFF) responded; however, the fire was extinguished before they arrived.

During an initial inspection, the maintenance staff discovered fire distress on the engine common nozzle assembly, underside of the wing, pylon, flap track fairings, spoilers, and flaps.

The initial examination of the incident airplane and engine occurred between November 9 to 12, 2017 at the Seattle-Tacoma Airport. Investigation team members including the National Transportation Safety Board, Federal Aviation Administration, Hawaiian Airlines, United Kingdom Air Accident Investigation Branch, R-R, and Airline Pilots Association were in attendance.

The engine was shipped to a specialized Rolls-Royce Trent engine overhaul facility, N3 Engine Overhaul Services (N3EOS) GmbH in Arnstadt, Germany where the team met between December 17 and 19, 2017 to remove specific external components that were identified during the field investigation in Seattle for detailed teardown, remove residual fuel from the lines between fuel powered components for examination and further examination the engine. Investigation team members including the NTSB, German Federal Bureau of Aircraft Accident Investigation, R-R, Airbus, and N3 Engine Overhaul Services were in attendance.

The fuel pump was examined at the Eaton facilities in Cleveland, Ohio on February 4, 2018.

The fuel oil heat exchanger (FOHE) was examined at the Sumitomo facilities in Osaka, Japan on July 10-12, 2018.

The variable inlet guide vane controller was torn down and examined at the United Technologies Aerospace Systems (UTAS) facility in Marston Green, UK on

October 17, 2018, and the torque motor was torn down and examined at the Moog facilities in Tewkesbury, UK on October 18, 2018.

D. DETAILS OF THE INVESTIGATION

D.1 Engine Description

The incident airplane was powered by two Rolls-Royce Trent 772B-60/16 turbofan engines. The Trent 700 series engine is a three-shaft, high-bypass-ratio, modular turbofan engine with low-pressure (LP or N1), intermediate-pressure (IP or N2) and high-pressure (HP or N3) compressors driven respectively by LP, IP, and HP turbines through coaxial shafts. The LP system consists of a single-stage, wide-chord, hollow fan blade compressor driven by a four-stage turbine. The IP system consists of an eight-stage axial flow compressor driven by a single-stage turbine. The HP system consists of a six-stage axial flow compressor driven by a single-stage turbine. The combustion system is an annular construction incorporating fuel spray nozzles (Figure 1).

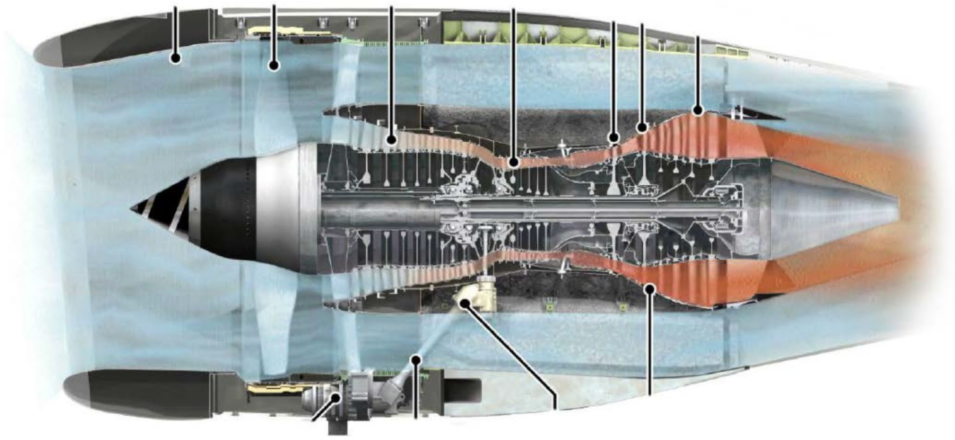

Figure 1 - Rolls-Royce Trent 700 Cross-Section

An external gearbox is mounted underneath the engine fan case and is used to drive fuel, oil, and hydraulic system pumps, electrical generators, and other accessories. The external gearbox is driven via a drivetrain driven from the engine’s HP spool. Engine starting is facilitated by spooling up the HP system by means of an air turbine starter motor mounted on the external gearbox. This engine features a full authority digital electronic control (FADEC) system with a dual channel, programmed engine electronic control mounted on the upper left-hand side of the engine fan case.

The Federal Aviation Administration (FAA) Type Certificate Data Sheet E39NE, Revision 7, dated April 25, 2019, states the engine has a takeoff thrust rating of 71,100 pounds at sea level static.

D.2 Engine History

The event left hand (LH or No.1) engine serial number (ESN) 42543, was built in November 2014. According to Hawaiian Airlines (HAL), the engine has accumulated 11879.4 hours, time since new (TSN) and 1,945 cycles since new (CSN) at the time of the incident. The event engine was the original engine installed on the event airplane on January 12, 2015 and was never taken off wing. A recently upgraded fuel metering unit (FMU) serial number (S/N) 702-03 was installed on July 27, 2017. The FMU had accumulated 260.5 TSN and 45 CSN. No other engine components were known to have been replaced.

The right hand (RH or No.2) 'sister' engine, ESN 42544, was also the original engine installed on the event airplane in January 2015.

D.3 On-Scene Examination

D.3.1 Review of the Engine Electronic Data Collected

D.3.1.1 Airplane Recording Devices

The Flight Data Recorder (DFDR), part number (P/N) 2100-4045-00, Cockpit Voice Recorder (CVR), P/N 980-6032-020, FDIMU, P/N 2234340-02-02 and QAR/DAR, P/N 2243800-362 were removed from the airplane and sent to the NTSB recorder laboratory in Washington, DC for download and analysis.

D.3.1.2 Aircraft Maintenance Data

The engine health monitoring (EHM), the aircraft communication addressing, and reporting system (ACARS) and the aircraft condition monitoring system (ACMS) data was reviewed, and the following observations were revealed.

ESN 42543 exceedance messages:
- 05:00:17 (UTC) N2 Redline Exceedance for 3 seconds
- 05:00:32 (UTC) N2 Redline Exceedance for 7 seconds
- 05:01:15 (UTC) N2 Over Limit
- 05:02:46 (UTC) N2 Redline Exceedance for 8 seconds
- 05:03:26 (UTC) Turbine Gas Temperature (TGT) Redline Exceedance

Each exceedance was approximately 104 percent (%) N2 speed.

The following observations were made from the findings:

1) A comparison of the variable stator vane (VSV) positions revealed that there was a large behavior difference between the LH and RH engines.

2) The P30[1] pressures of LH and RH engines were both equal and stable; however, while the VSV positions on the RH engine corresponded to the VSV demand, the LH engine exhibited large variations and did not correspond to the VSV demand.
3) VSV variations directly impact N2 speed and the high angle of the LH engine VSVs directly increased the N2 to overspeed.
4) The fuel flow (FF) did not correspond to the engine speed increase during the overspeed events, indicating that the electronic engine control (EEC) was not commanding the overspeed.
5) The variation in engine pressure ratio (EPR) did not correspond to the FF variation, indicating that the FF was not the significant cause of the EPR variation.
6) The EEC did not stop the overspeed occurrences because its logic only intervenes above 114%.

Because of these findings, the fuel metering unit (FMU), EEC and VSV control system were closely examined.

D.3.1.3 Maintenance Post Flight Report (MPFR)

The MPFR data was reviewed, and it was noted that there were error codes referring to the VSV failure, Engine 1 control system fault, Engine 1 N2 overlimit, EEC fault codes, P30 pressure tube, Engine 1 shut down, Engine 1 exhaust gas temperature (EGT) overlimit, Engine 1 oil chip detector.

D.3.1.4 Airport Video Review and Notes

Seattle-Tacoma International Airport (SEATAC) Airport Operations was contacted, and airport videos were obtained for further analysis. A preliminary review of the video showing the aircraft landing, revealed:

1) The fire started after the airplane landed and stopped just as the airplane came to rest on the runway.
2) The flame development signature at the tailpipe did not match the typical characteristics of an engine surge[2]; however, a review of the engine parameters indicate that an internal surging was occurring throughout the landing roll.
3) The review of the video recording showed a relatively slow billowing flame, which started at the tailpipe of the engine and traveled backwards, under the wing. Once all the fuel was consumed, the fire extinguished, whereupon a new billowing flame front started again at the tailpipe.

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[1] P30 pressure is the engine internal air pressure at the 3.0 stage in the compressor.

[2] Surge is a response of the entire engine which is characterized by large fluctuation in engine pressures with significant airflow reduction or reversal in the engine pressure and flow.

D.3.2 Event Timeline Data Review

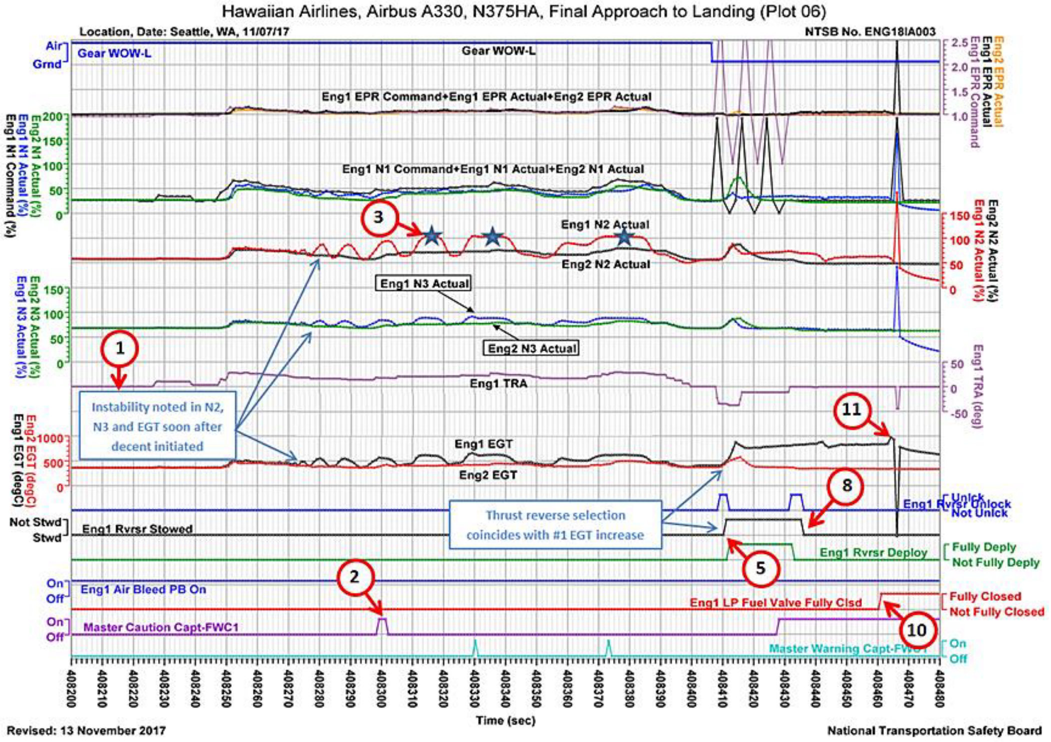

Figure 2 - DFDR Engine Parameter Plot of Event

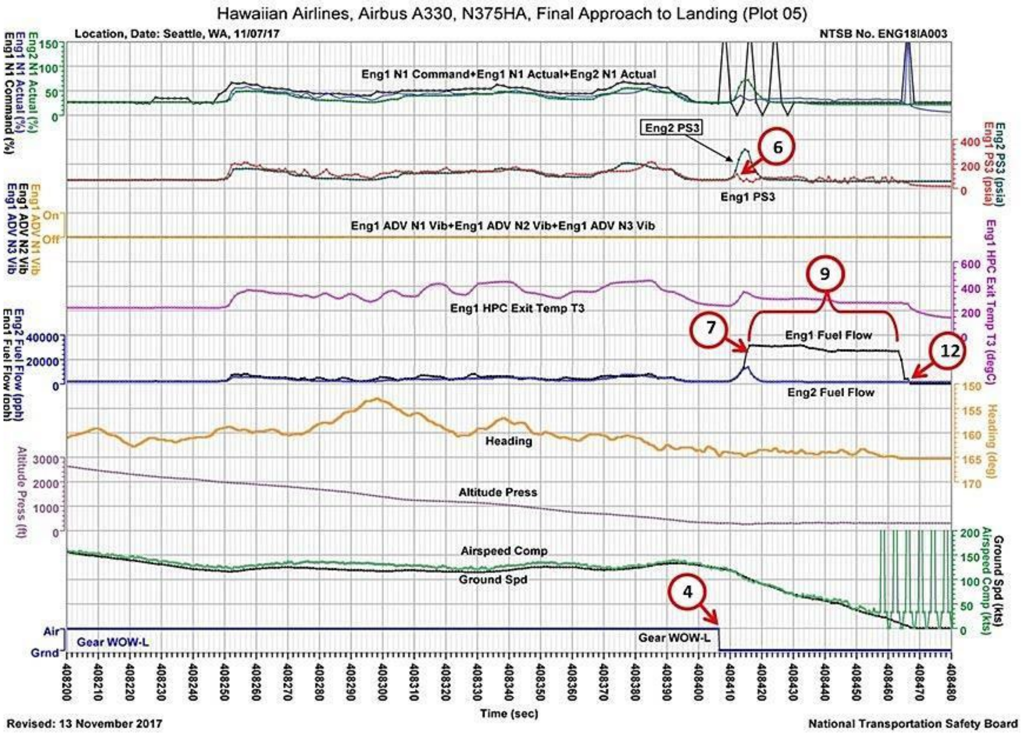

Figure 3 – DFDR Engine Parameter Plot of Event

The DFDR was sent to the NTSB recorder laboratory where it was downloaded and the plot on Figure 2 & Figure 3 prepared. A review of the significant occurrences was noted and highlighted on the plot and descriptions of the occurrences were made on Figure 2 & Figure 3.

Reference No. on Figure 2 & Figure 3	Condition	Comment	Time
1	Engine instability evident in N2, N3 and EGT	Instability appears to be cyclic	
2	ENG CTL SYS FAULT with VSV SYSTEM / VSV CONTROL UNIT messages set	VSV position difficult to achieve, aircraft ECAM message inhibited on final approach	
3	VSV actual and demanded positions disagree during descent	3 times N2 overspeed alerts with VSV becoming increasingly sluggish	05:01:15
4	Aircraft landed	Engine power to idle	05:01:48
5	Full reverse thrust selected; Engine EEC controlling in N1 mode, VSV's no response	Fuel flow rises to approx. 32K pounds per hour (pph) (maximum) in an attempt to achieve demanded N1	05:01:51
6	N3/P30 mismatch due to high fuel flow and slow N3 speed	P30 pipe failure set – Surge detection function inhibited	05:01:56
7	Core engine surges	P30 drops	
8	Reverse thrust cancelled. Engine EEC transfers control from N1 to N3 mode	N3 actual 67% and within EEC expected levels, therefore high fuel flow maintained	05:02:14
9	Taxi. FWD idle, high TGT and FF	Repeated surges, ignition of unburnt fuel exhausted from jet pipe. ATC notifies crew	
10	TGT exceeds 900 °C	EEC reduces FF	05:02:43
11	Pilot operates fire handle	Airplane LP fuel (spar) valve closes although engine continues to burn downstream fuel	05:02:46
12	Pilot selects engine master lever to off	Shut down - HP fuel valve closes	05:02:47

Figure 4 – Event Timeline Notes

Additionally, a review of the data that was obtained from the N2 exceedances on the R-R reports and plotted (Figure 5) revealing that during descent:

- N2 exceedance #1 occurrence at 05:00:17 UTC; 6 seconds to respond
- N2 exceedance #2 occurrence at 05:00:32 UTC; 10 seconds to respond
- N2 exceedance #3 occurrence at 05:01:15 UTC; >12 seconds to respond

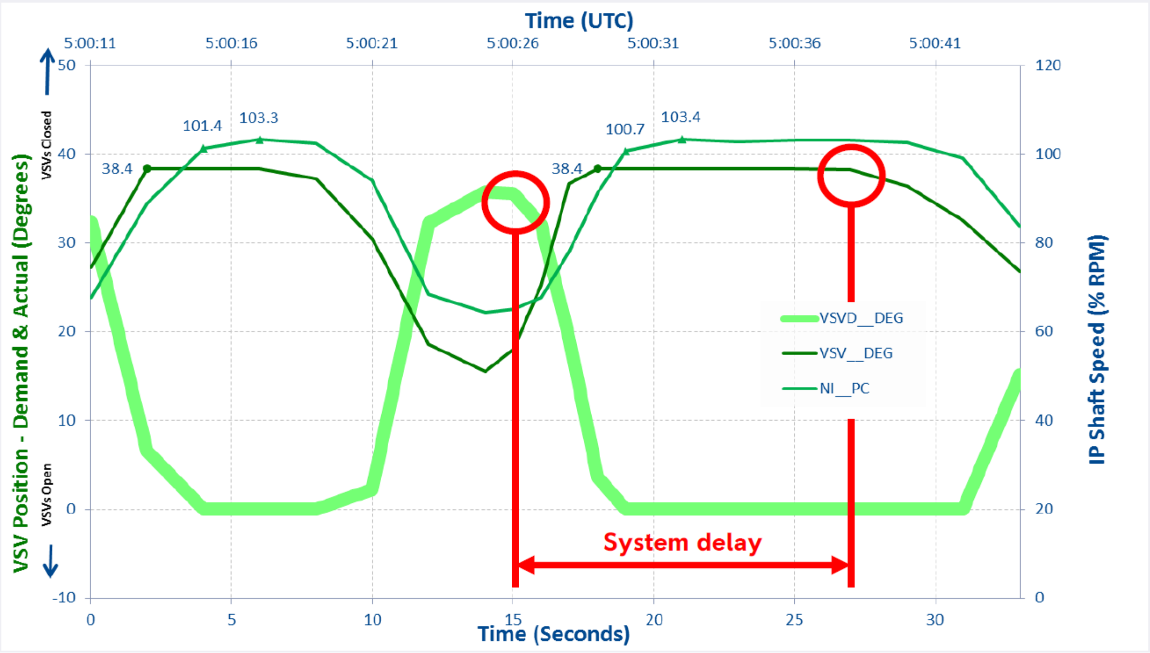

Figure 5 – Plot Showing VSV Demand and Actual Position – Note Delay (Courtesy R-R)

D.3.2.1 Review and Findings of Event

1) During descent VSV control was slow to respond and engine became increasingly unstable.
2) The electronic centralized aircraft monitor (ECAM) message ENG1 CTL SYS FAULT “avoid rapid thrust change” message inhibited as aircraft on final approach permitting full reverse thrust application.
3) Aircraft landed at - 05:01:48.
4) Full thrust reverse was selected at - 05:01:51 – It is noted that during reverse thrust operation, the EEC logic controls in N1 mode. The VSV system did not respond to engine power selection, and FF increased to maximum output at about 31,600 pph to achieve the demanded N1 speed. This would indicate that flames from the engine tailpipe had not occurred until after the aircraft had landed.
5) Little or no response from VSV system to commanded thrust resulted in restriction to core airflow and suppression of N1 speed.
6) Simultaneously the resultant N3/P30 mismatch triggered P30 pipe failure detection, which inhibited the engine surge detection function.

7) The EEC commanded an increased FF to maximum of about 32K pph in an attempt to achieve the demanded N1, incorrect VSV position resulted in engine surge - 05:01:56.
8) Unburnt fuel continued to ignite at and behind the engine tail pipe.
9) Thrust reverse cancelled and EEC logic changed engine governance from N1 to N3 control - 05:02:14.
10) At this point N3 speed, which was within the specified EEC synthesized levels, stagnated at about 67%, and the control system logic maintained the high FF delivery.
11) The engine continued to surge, and the airport closed circuit TV (CCTV) footage indicated that unburnt fuel continued to ignite to the rear of the engine tail pipe.
12) TGT exceeded 900°C and EEC reduced the FF at 05:02:43.
13) FF demand was only reduced when the EEC detected an engine TGT exceedance, and shortly afterwards the flight crew shut the engine down.
14) Pilot made aware of tail pipe fire by ATC and engine was shut down using the fire handle (aircraft low pressure spar valve closes) - 05:02:46.
15) Engine master lever selected "off" and engine shutdown - 05:02:47.

Analysis of the VSV positional data taken from the N2 exceedance reports observed a disagreement between the demanded and actual position of the VSVs, to a point where control was lost. Further assessment noted the VSV response time had become increasingly sluggish for each N2 exceedance (see Figure 5).

D.3.3 General Airplane Examination

Initial examination of the event airplane and engine occurred from November 9 - 12, 2017 at the SEATAC. Investigation team members including the NTSB, FAA, Hawaiian Airlines, UK AAIB, R-R, and ALPA were in attendance. The left-wing external composite panels on the common nozzle assembly, lower panels of the flaps, and flap track covers had evidence of burn patterns and blistered paint consistent with unburnt fuel vapors igniting towards the back of the engine (Photo 1 & Photo 2).

The event engine was detached, lowered from the airplane, placed on an engine stand, and moved to a secure area. The engine was externally intact and undamaged. The fan could be turned with normal effort and when turned, no grinding or other abnormal sounds could be heard emanating from the engine core. The engine pylon mount hardware was intact and undamaged. There were no leaks in any of the oil or fuel lines.

The engine was externally clean. There were no signs of mechanical or thermal distress (Photo 3). The fan cowls and thruster reverser cowls were undamaged and clean.

The front spinner cone was undamaged and exhibited only operational erosion of the paint. The last stage of the LP turbine was undamaged. There was no obvious unusual discoloration on the LP turbine blades.

The fan blades were undamaged. The fan case track liner was undamaged and showed no evidence of scoring (Photo 4). The fan was not further disassembled or examined.

The common nozzle assembly was intact, however; there was evidence of oily soot at several locations. There was a dislocated panel at the 2 o'clock location that displayed heat distress (Photo 5). The external surface showed evidence of heat distress at the 9 o'clock position consisting of light blistering and discoloration of the paint surface.

The scavenge oil filter and LP fuel filter were removed, examined, and found to be in an unremarkable, nominal clean condition. An Engine 1 chip detector note was highlighted in the Maintenance Post Flight Report. A very small sliver was noted crossing the detector bands.

Samples of engine oil and fuel were retained and sent to the NTSB local office for temporary storage. The fuel sample was drained from the engine fuel pump. A visual examination of the LP fuel filter revealed no evidence of contamination.

A borescope inspection of the entire rotating group was performed and included the LP turbine, high-pressure nozzle guide vanes, HP turbine, combustion section, HP compressor, IP compressor, and IP turbine. All rotating group components appeared to be intact and undamaged. Sooting was observed on the combustion chamber, high-pressure nozzle guide vanes and the HP turbine blades. Some leading-edge nicks were observed on the HPC stage 2 blades, however; it could not be determined if they were a result of this fire event or if they were from previous operation. Some loss of coating was observed on the leading edges of some IPT blades.

An external visual inspection of the VGV system found no obvious damage or distress. The VSV rams were disconnected from the unison rings to enable the independent movement of the vanes. The movement of the assembly was noted to be consistently smooth throughout the range with minimal input load.

D.3.3.1 Intermediate Pressure Compressor (IPC) and VSV Actuating Mechanism Tests

Description

The engine has two fuel-pressure (fueldraulic) actuated rams (Figure 7) that control the VSV unison rings: one at approximately 3 o'clock[3], the other at approximately 9 o'clock.

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[3] All directional references (front, rear, right, left, top, bottom, clockwise, counterclockwise) are made aft-looking-forward (ALF) unless otherwise specified. All numbering is in the circumferential direction, starting with no. 1 at or immediately clockwise from the 12 o'clock position and progressing sequentially clockwise ALF.

Tests

This system was inspected and tested using the instructions contained in engine manual (EM) 72-32-42-200-800. All the actuator fuel tubes, harness connections and looms were undamaged.

The static positions of the rams were measured (Photo 6). On the LH (event) engine the distance measured between the inboard ram collar flange and the ram housing was 45.5 millimeters (mm) for both actuators. As a comparison, the RH engine static actuator locations were measured to be 58 mm. According to the Goodrich Engine Control Systems Component Maintenance Manual, the piston travel is 58.51 mm. The actuator on the LH engine was more extended than on the RH engine, which corresponds to a higher power condition.

A test to determine the condition of the VSVs and the VSV unison ring system was performed. The ram-to-unison ring coupling was disconnected, and a special handle shaped tool was connected to the VSV linkage allowing hand effort to actuate the VSV unison system. The motion was consistently smooth in both directions, requiring little effort (approximately 5 pounds (lbs.) applied to the top of the handle). No functional abnormalities could be found in the VSV actuating systems.

D.3.3.2 Electrical Resistance Test of the VSV Actuator Internal Coils

Description of the VSV Actuators

Two identical VSV actuators (Ref: Figure 7) provide the power to move the VSV mechanism to the required position. The actuators are powered by high-pressure (HP) fuel from the VSV actuator control valve and there are separate fuel lines to the ‘extend’ and ‘retract’ sides of the actuator. There is also a fuel drain line to collect fuel that leaks past the actuator seals.

Each actuator is connected to the unison rings via an adjustable bellcrank linkage. The unison rings then connect to the individual VSV airfoils via a lever arm.

Each VSV actuator assembly contains an internal linear variable differential transducer (LVDT) which is used by the EEC to determine the feedback position of the actuator rams. The LVDT contains three coils which can be electrically measured by an ohmmeter. The procedure number is 75-33-00-810-807-a in the Airbus A330 troubleshooting manual. All resistance measurements fell within the AMM specifications and not faults were found.

D.3.3.3 VSV Controller Electrical Test

Description of the VSV Controller System

The VSV Controller was P/N 1875MK5 and it was manufactured by Lucas Engine Control Systems. The VSV controller positions the VSV actuators by using HP fuel. It contains two torque motor assemblies and two internal coils. The VSV controller converts (Figure 6) the electrical demand signals from the EEC to a fuel hydraulic control pressure. This pressure moves the VSV actuators to the commanded position. The VSV actuator control valve receives signals from either channel A or channel B of the EEC, which positions a torque motor within the valve to control the supply of HP fuel in the extend and retract lines of the actuators. The system is fully modulating and will change position according to the corrected N2 speed, as commanded by the EEC.

VSV Control unit resistance checks were done according to the airplane maintenance manual (AMM) 715000200803. The resistance of channel A was 30.8 Ohms (Ω) while channel B was 30.4 Ω, both within the 29 to 35.5 Ω limit. No electrical faults were found in the VSV controller.

D.3.3.4 VSV system electrical harness continuity checks

The VSV harness is the electrical wiring bundle that connects the VSV electrical connectors to the EEC connectors. Two tests were done: One to test the wiring continuity and the other to test the insulation. The VSV system electrical harness continuity checks were done according to AMM 715000200802 and the VSV system electrical harness insulation resistance checks to AMM 715000200803. No faults were found in either system.

D.4 Engine Externals Examination and Findings

The engine was shipped to a Rolls-Royce Trent engine overhaul facility, N3 Engine Overhaul Services GmbH in Arnstadt, Germany where the team met between December 17 and 19, 2017 to remove specific external components that were identified during the field investigation in Seattle for detailed teardown, remove residual fuel from the lines between fuel powered components for examination and further examine the engine. Representatives from German Federal Bureau of Aircraft Accident Investigation (BFU), Rolls-Royce, and Airbus were present for the examination.

Because of the findings from the field examination of the engine in Seattle, Washington, as well as the analysis of the digital data, the investigation focused on the following parts or systems (Ref: Figure 6):

- Fuel metering unit (FMU)
- EEC and power control unit (PCU).
- VSV controller and the RH and LH VSV actuators

- FOHE and LP fuel filter
- Fuel Pump (an assembly, consisting of the HP and LP pumps)
- High pressure (HP) filter – 70 micron (µm)

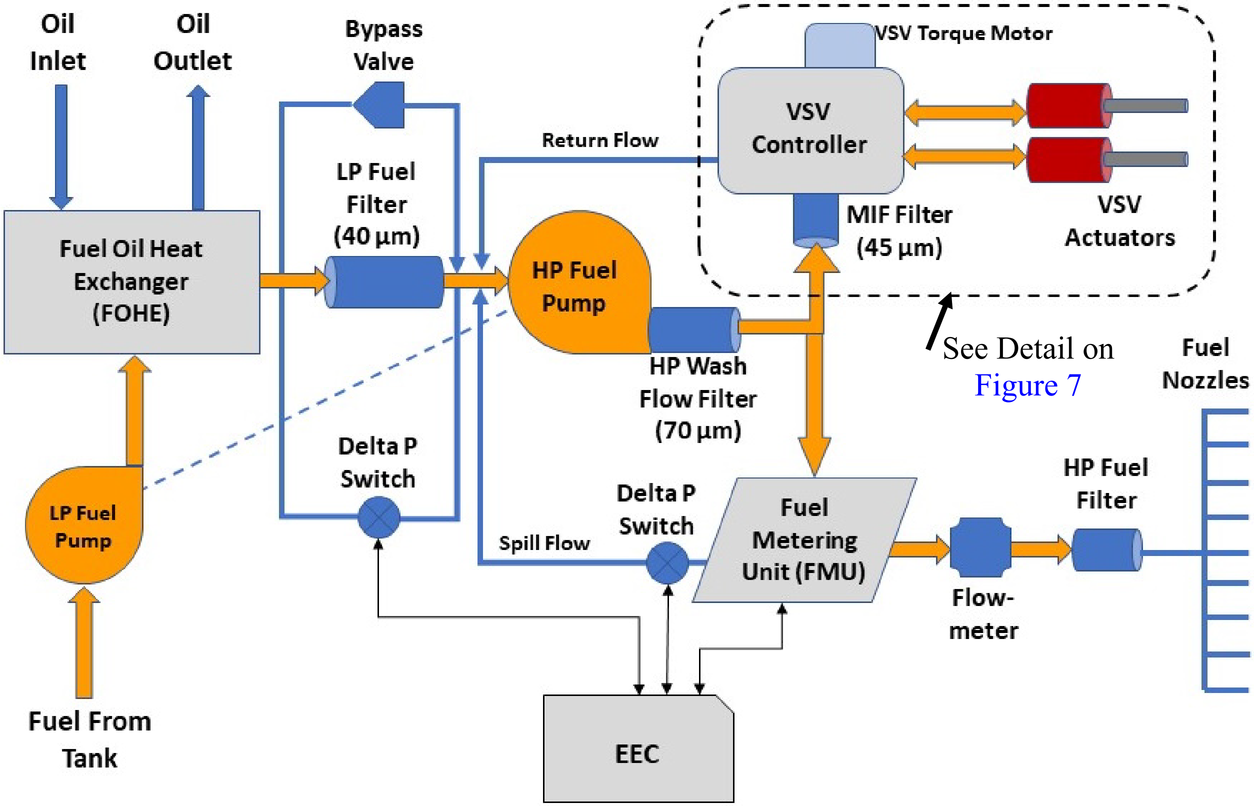

Figure 6 - Overview of Engine Fuel System (See Detail of VSV Controller System Schematic in Figure 7)

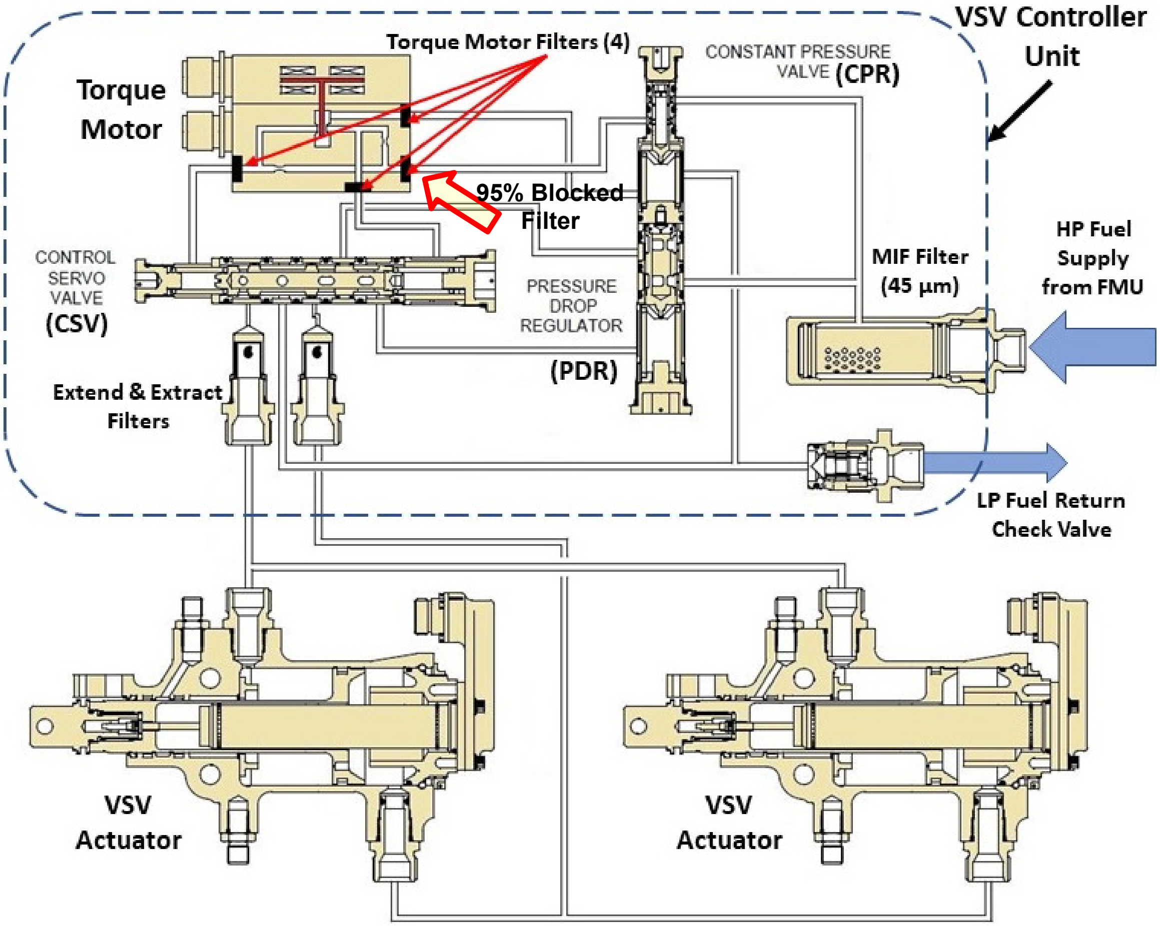

Figure 7 – VSV Control System Schematic

D.4.1 Variable Inlet Guide Vane (VIGV) & VSV Control System Description

The variable inlet guide vanes direct air into the intermediate pressure compressor at the correct angle-of-attack to avoid compressor surge and stall while maintaining optimum engine efficiency. A single stage variable inlet guide vanes are located immediately behind the engine section stators. A further two stages of variable stator vanes are located after the first and second stages of the intermediate compressor.

A variable stator vane control system operates the variable inlet guide vane system by receiving an electrical signal from the EEC that sets positional demand to match the demanded engine power condition. The torque motor responds by directing servo fuel to either side of the control servo valve to extend or retract the VSV actuators to the required position. Each actuator has an integral Linear Variable Differential Transducer (LVDT) to provide positional feedback to the EEC.

D.4.2 FMU (Ref. Figure 6)

The purpose of the FMU is to control the flow of fuel to the fuel spray nozzles and combustion chamber from electrical inputs from various control units. The EEC is the primary control, but other inputs from the Overspeed Protection Unit (OPU), flight deck engine fuel control switch and fire handle also have inputs into the unit.

The event engine's FMU was a modified unit replaced 1,240 hours and 220 cycles prior to the event. Because the unit was modified and not overhauled at the vendors, the related torque motor (TM)'s supply port filters would not have been inspected or replaced. This resolves the confusion on why the TM supply port filter was 95% blocked after having only 10% of the service life of the VSVC TM (Ref: Figure 9). This unit had no previous maintenance done during its 13,9355 hours' TSN and 2,267 CSN service life.

The FMU was scanned using computerized tomography (CT) at Rolls-Royce, Bristol facilities and no evidence of internal damage or anomalous features was found, so it was shipped to UTAS for a teardown and examination without functional testing.

Fuel samples were taken from the unit for further analysis. The fuel contained fine black particulates and black deposits were also observed in the HP inlet port, flow wash filter, and drain plug region. The level of contamination within the unit was above the levels normally observed during vendor overhaul.

Electrical testing of the unit confirmed the main metering valve, shut-off valve, turbine overspeed, and linear variable differential transducer functions all met the component maintenance manual (CMM) test requirements. No further testing was done.

The FMU TM supply filter was 95% blocked with further debris in the unit body (See Figure 9).

D.4.3 EEC (Ref. Figure 6)

The EEC is a dual channel digital unit located on the LP fan case of the engine, and in normal operation, only one of the two channels is in control. In the event of certain failures, this control is transferred to the alternate channel, being either channel A or B. Movement of the aircraft throttle levers generates a command signal for the EEC. The EEC converts this signal to an Engine Pressure Ratio (EPR) value or N1 value (when in N1 control mode). VSV scheduling is a function of compressor airflow. This is calculated by the EEC, using measurements of rotor speed (N2) and air pressure (P30). The EEC performs a VSV sweep check on engine starting and engine shutdown and tests the speed of operation of the VSV actuators and alerts maintenance of an impending failure if the time is longer than specified causing action to service the VSV system. The EEC did not issue any warnings of an impending blockage of the supply port fuel filters within the TM, considering the 95% blockage of the filter.

The EEC was removed in Seattle and sent to UTAS in Marston Green, Birmingham, UK for inspection and test. A visual EEC inspection found the unit to be in good condition with no obvious signs of damage, and the unit passed the bonding strap checks.

The download of the non-volatile memory (NVM) from both channels A & B was completed successfully. Review of the fault store found the initial EEC fault set during the last flight was for a slow VSV torque motor response, which coincided with the momentary ENG 1 CTL SYS FAULT warning in the cockpit. The fault store from previous flight history had nothing obvious to suggest there was an impending system issue. It was noted that the cockpit ECAM warning "ENG1 CTL SYS FAULT" with the associated message "avoid rapid thrust changes" was observed by the flight crew during approach. However, the aircraft system subsequently suppressed the ECAM fault warning to reduce the flight crew workload during demanding phases of flight. UTAS stated that these faults normally relate to filter blockage, or slow response of the VSV controller, constant pressure valve (CPV), pressure drop regulator (PDR) or the actuator control valve (ACV) itself due to debris or surface lacquering.

EEC NVM data interrogation also confirmed a number of other faults associated with reduced / loss of VSV control, including -

a) N2 redline limit exceedance.

b) P30 pressure tube leakage / blockage – N3/P30 mismatch (actual reading and not a tube fault).

c) EPR shortfall – Engine control limiting power due to maximum limit.

After the data download from the EEC was completed, an ambient, thermo-cycle and vibration test, was done with no faults found. No further testing was done.

D.4.4 PCU (Ref. Figure 6)

The PCU is located adjacent to the EEC and converts 115-volt (V) alternating current (AC) aircraft electrical power supply and engine dedicated generator output to 22V direct current (DC) for use by the engine EEC.

The power control unit was sent to UTAS in Marston Green, Birmingham, UK for test, the results of which were:

- Isolation Test - Passed
- Bonding Test - Failed one test point from the rear bond strap to JA27 connector. The high limit was 2.5mV and the actual reading 2.62mV
- Ambient temperature, Cold & Hot - Passed
- Burn-in 1 Cycle – Passed
- Vibration Test - Passed

According to the manufacturer, a variation of 0.12mV would no effect on the functionality of the unit, it is normally grounded through the connectors that are tested during the functional test, which the unit passed. The unit was returned to service after test.

D.4.5 VSV Controller (Ref. Figure 6 & Figure 7)

The VSV controller was P/N 1875MK5 and S/N SAA14-439 and had accumulated 11,879 hours TSN and 1,945 CSN. The VSV controller was the original unit fitted to the engine on entry-into-service with no removals for repair recorded.

The VSV controller (Photo 7 & Photo 8) and VSV actuators (Photo 9 & Photo 10) were removed from the engine with no difficulties. The VSV controller, VSV actuators and FMU were sent to R-R Bristol for CT scanning, after which they were transferred to the manufacturer, UTAS, in Marston Green, Birmingham England for teardown and examination. The CT scan of the VSV controller and actuators revealed no evidence of internal damage or anomalous features, so they were forwarded to the manufacturer, UTAS at the Marston Green facilities, England for a teardown and examination without functional testing.

D.4.5.1 The Control Servo Valve (CSV) (Ref. Figure 7)

There was no binding or resistance to movement of the CSV (Photo 11). The CSV contained very fine black debris particles. Brown staining was found in the outboard side control valve. There was no significant level of lacquering[4]. The valve was not examined further.

D.4.5.2 The Constant Pressure Valve (CPV) and Pressure Drop Regulator (PDR) (Ref. Figure 7)

The CPV and the PDR contained very fine black debris particles. Dark staining was observed around the end of valves. There was slight wear to side of pistons, which, according to R-R, was consistent with this amount of service time. There was no significant level of lacquering. The valve was not examined further.

D.4.5.3 The Extend and Retract Filters (Ref. Figure 7)

The extend and retract filters were clear of contamination. They were not further examined.

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[4] Fuel Lacquering - Depending on various factors, such as fuel quality, temperature, fuel stagnation, or chemical contamination, lacquer deposits, which consists of a thin (10-20µ) thick hard layer that is mostly amber in color. Its presence can restrict the free movement of fuel valves or other components in the fuel system.

D.4.5.4 The LP Return Check Valve (Ref. Figure 7)

The LP return check valve was clear of contamination. It was not further examined.

D.4.5.5 The Main Inlet Filter (MIF) (45µ) (Ref. Figure 7)

The MIF filter (45µ) showed no visible distortion or breaching of the filter element and was remarkably clean (Photo 12), considering it was just upstream of the contaminated torque motor supply port filter. The MIF from the sister engine (s/n 42544) was removed from the engine and both were shipped to R-R Derby for a more detailed analysis.

Both MIFs were backflushed, and the debris was recovered in a fine laboratory filter, revealing a marked difference of captured debris. Significantly more debris was recovered from the sister engine compared to the event engine (Photo 13). The captured debris consisted primarily of carbon (C), oxygen (O), sodium (Na), and sulfur (S). Other elements present included iron (Fe), nickel (Ni), zinc (Z), aluminum (Al), silicon (S), magnesium (Mg), and copper (Cu), all consistent with component wear.

According to R-R, under normal conditions, TM filters near the end of their useful life, still operate normally even in the range of 92-95% blockage. As the filter reaches 97% in a gradual manner during regular operation, the gradual slowing behavior of the VSV actuators trigger an error warning from the EEC.

Compared to field experience of other engines this clean MIF was inconsistent with its time in service. Evidence of contamination of aluminum sulfate (also known as alum[5]) was found in the VSV actuators (See D.4.6 Left and Right VSV Actuators) and the LP fuel filter (See D.4.7.1 LP Fuel Filter). The presence of alum provided evidence of free water within the system, with the water providing the main driver for the potential "cleaning" effect of the MIF, sending a cloud of higher concentration of debris to the downstream TM supply filter causing a sudden increase in blockage instead of predictable gradual operational change.

R-R controls specialists performed a Trent 700 database trawl of VSV control issues, revealing that VSV faults were almost always caught by the EEC checks on the ground during start or shutdown. In comparison, the thrust instability on the event engine occurred in cruise/landing phases of flight and different to "normal" experience with this type of fault, indicating a sudden anomaly rather than normal gradual behavior.

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[5] Aluminum Sulphate is a water-soluble coagulant commonly used in water purification. It is also used in the paper manufacturing industry. Aluminum sulphate is not a compound that is used in the aviation industry.

D.4.5.6 The Torque Motor (TM)

The TM operates via an EEC input signal, which energizes the coil in the unit which moves the flapper valve assembly between two nozzles. In the neutral or null position, the pressure output to the CSV is equal and the actuator rams remain static. As the flapper moves away from one of the control nozzles the fuel pressure on one side of the CSV reduces, causing the control piston to extend or retract the VSV actuator rams. The gap between the contacting faces is very small.

The schematic on Figure 7 depicts the location of the TM in the system, while Figure 8 depicts a cross section of the TM. The event engine's TM was P/N 77879199 and S/N E2580H, the original unit fitted to the VSV controller and had been in service for 11,879 hours TSN and 1,945 CSN. The TM is a component of the VSV controller assembly (Ref: Photo 8) and is separately manufactured by Moog and affixed onto the VSV controller body, which is manufactured by UTAS.

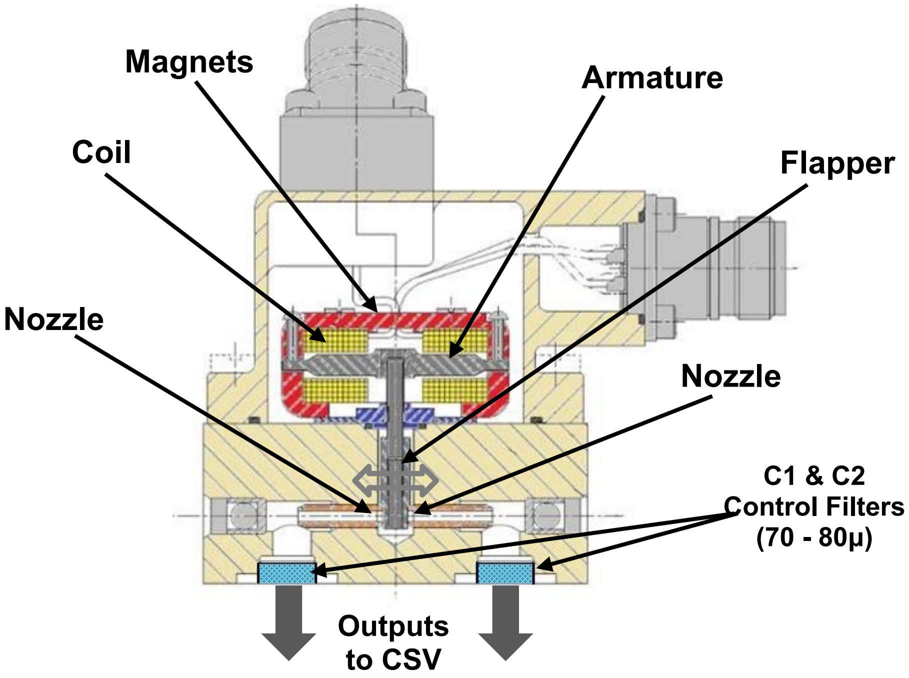

Figure 8 – VSVC Torque Motor Cross Section. Note: The Input Fittings and Blocked Supply Filter are not Shown in this View. (See Figure 7 that shows the Input Fittings, Filters and Identifies the Blocked Filter)

Initial R-R examination of the TM revealed significant contamination of the supply port filter (70 - 80µ) outer element (Photo 14). The TM was shipped to the manufacturer Moog in Tewkesbury, England for further examination which was performed on October 16, 2018.

A detailed visual inspection found the TM supply port filter had significant accumulation of debris that was adhered on the supporting mesh and filter element of the VSVC supply port filter (Photo 15). Backlight assessment of the filters visually confirmed both the supply and return port filters were 95% blocked with contamination. It was noted that the debris accumulation was adhered to the supporting mesh and element rather than being settled on the upstream side. A scanning electron microscope (SEM) energy dispersive x-ray (EDX) material analysis found its composition to include metallic elements (Cu, Fe, Ni and Cr) combined with fuel breakdown products (C, O, S and N). According to UTAS and MOOG, filter blockage with operational age is a known phenomenon.

ESN	Unit	Hours/ Cycles	TM Filter	% Blockage (Backlit)
42543 Event Engine	VSV Controller	11879 / 1945	Supply Port (SP)	95%
			Return Port	
			C1 control	0%
			C2 control	0%
			SOV Supply Port	5%
42544 Sister Engine	VSV Controller	12820 / 2078	Supply Port	95%
			Return Port	50%
			C1 control	0%
			C2 control	0%

Figure 9 - Filter Blockage Summary – Note: Only supply port filters in units were significantly blocked.

The VSVC TM supply port filters of the sister engine, ESN 42544 were also removed, inspected, and compared to the event engine, revealing a similar filter blockage of 95%; however, the captured debris was not adhered to filter support mesh as observed on the event engine but rather the debris was mostly settled on the element itself (Photo 16).

The FMU FMV TM supply filter was approximately 95% blocked (Photo 17). An SEM EDX material analysis found a similar elemental composition of the debris as in the VSVC supply port filter.

An SEM analysis revealed the debris was predominantly fuel breakdown products combined with metallic material.

The TM unit was disassembled, and debris was also found on the flapper face on the C2 control nozzle side (Photo 18). The flapper valve faces exhibited bright circular witness marks consistent with normal contact with the control nozzle; however, radial ‘sun ray’ stain marks were seen around the circular witness marks (Photo 19), consistent with debris that had been trapped between nozzle and flapper. Black particulate debris was recovered from the rear of the C2 control nozzle. An SEM scan of the flapper debris revealed that it consisted of larger particles that were coated with agglomerated material (Photo 20). An analysis of the debris found evidence of Fe, Cr, Ni, V and Cu.

General Findings:

The VSVC TM supply port filter contained significant contamination and was 95% blocked, restricting the fuel flow thereby slowing the VSV actuators down.

It was noted that despite the finer LP filter (40µ) and a HP fuel filter (45µ) being upstream, the comparatively coarse (70 - 80µ) TM SP filter contained particles of debris that were larger than 45µ that were agglomerated on the filter element.

A review of the upstream components that had wear type operation with similar elemental composition, identified the HP pump gear (Fe - 82%, V - 10%, Cr - 6% and Mo - 1.3%), HP pump bearing (Cu - 90%, Sn - 5%, Zn - 3% and Pb - 2%) and the FOHE by-pass valve (Fe - 71%, Cr - 18%, Ni - 9%, Mn - 2%) as possible sources of the particles. The particle sizes were smaller than the 10µm, which is below the upstream filter capability of 45µm for the HP fuel filter and the 70µm HP wash flow filter and therefore could enter the VSV TM filters and flapper area; however, if they remained as individual particles they would normally pass through the area. As agglomerations with adhesive qualities, they became attached to the VSV TM SP filter and likely were the reason for blockage. The adhesive behavior of the particles as observed on the filter could not be positively determined; however, the NTSB has become aware of some fuel quality studies have been performed by other airframers in the industry that have concluded that jet fuel available on the United States west coast contains up to seven times higher levels of sulfates than east coast fuel. It has been noted that sulfate loading on fuel screens is routinely observed both on fuel component screens and on engine fuel filters of other engine installations.

D.4.6 Left and Right VSV Actuators (Ref. Figure 6 & Figure 7)

The VSV actuators were both P/N 1876MK3; the L/H was S/N SAA14-456 while the R/H was S/N SAA14-462. The two fueldraulic actuator units were the original units fitted to the event engine since new and both units had accumulated 11,879 hours TSN and 1,945 CSN. They were disassembled and examined (Photo 21).

A CT scan was performed on both units with no anomalous features found on either unit. Electrical testing of both actuators confirmed the LVDTs to be within specifications.

Actuator motion tests found that the force required for movement of the ram was 285 newtons (N), significantly higher than a nominal actuator, which requires approximately 230N force.

Both actuators were disassembled, and an examination revealed no evidence of damage or binding to any of the individual components. The internal fuel-washed surfaces were found contaminated with translucent globular deposits (about 200µm in diameter) (Photo 22) and fine black particulates were found on LVDT housing inner diameter, piston stop and jack piston chamber. This finding is inconsistent with super absorbent polymer (SAP)[6] contamination which is typically smaller in diameter at approximately 50µm. The globules turned white when dried (Photo 23 & Photo 24) transforming into hollow white friable shells. The initial analysis indicated an inorganic compound consisting predominantly of aluminum and oxygen with minor levels of sulfur and chlorine. A subsequent lab analysis confirmed the chemical composition to be aluminum sulphate ($Al_2(SO_4)_3$), also known as alum a chemical that is not used in the aviation industry and is not a component in fuel. The presence of the aluminum sulphate in the VSVA's is evidence that free water was present. The alum was dissolved in the water and dried to form the globules/spheres upon drying. Aluminum sulphate is not soluble in fuel and more would have likely been captured by the LP fuel filter if not dissolved in water (Note: traces visible at high magnification were evident in the LP fuel filter. However, these were only identified following a more detailed, technical assessment. The source of the alum in the fuel system could not be discovered. A closer examination of the surfaces of the jack piston revealed a mottling of the anodized surfaces (Photo 25). It was observed in the locations of the white deposits, that once they collapsed, some of the alum remain bound to the underlying mottled surface damage (Photo 26), implying a connection between the alum contamination and the corrosion observed on the anodized surfaces. R-R performed initial lab tests which confirmed that the presence of alum in water will increase the acidity levels due to the formation of sulfuric acid. It is undetermined if sulfuric acid in the water will increase the acidity of the fuel. No further chemical studies were performed. However, it should be noted that not all the anodized components within the VSC actuator were similarly chemically attacked, i.e., the piston stop.

D.4.7 FOHE & LP Fuel Filter Assembly (Ref. Figure 6)

The FOHE housing also incorporates the LP fuel filter housing and a spring actuated bypass valve, which is intended to open in the case of a blocked fuel filter. Two pressure differential transducers on the housing, sense and alert the pilot of the impending blockage of the LP filter.

D.4.7.1 LP Fuel Filter

Examination of the LP filter-to-HP inlet transfer tube revealed that it contained some fine metallic particles (Photo 27), which, because it is downstream of the LP fuel filter, was consistent with a failure of the LP fuel filter. Therefore, the LP fuel filter was

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[6] Most fuel uplifted into commercial aircraft flows through a filtration system which is designed to remove both water and solids. The water is removed from the fuel through absorption in Super Absorbent Polymer (SAP) or sodium polyacrylate.

removed from the FOHE and examined, revealing a small amount of fine, shiny, metallic debris on the upstream pleats (Photo 28). When the filter media pleats were spread apart for inspection, the filter media easily fractured in a brittle manner, making it impossible to perform a functional test of the filter media. According to R-R, the filter element brittleness was not an unusual observation for high-time filters.

The filter element was examined by the Rolls-Royce laboratory, where the debris analysis confirmed fine black carbon-based deposits, which included copper and sulphur particulates. A more detailed assessment and SEM analysis of the filter element from the engine found evidence of very small and fine spherical contamination, similar to that observed in the VSVAs. Chemical analysis revealed the composition to be aluminum, sulfur, and oxygen consistent with alum (Photo 29). R-R stated that the levels of fine debris observed were consistent with the service life of the elements of 4491 hours, however the presence of alum was not. The source of the alum could not be determined.

The filter element of the sister engine ESN 42544 was also removed and examined, revealing evidence of alum contamination.

D.4.7.2 FOHE

The event engine FOHE was the original unit fitted at entry-into-service and had completed 11,879 hours TSN and 1,945 CSN.

The FOHE was removed and examined (Photo 30). The bypass valve was removed from the FOHE housing, and the sealing surfaces examined, revealing a worn ring from contact wear on the seat (Photo 31) and witness marks on the conical face (Photo 32). The FOHE was shipped to Sumitomo Precision Products in Amagasaki, Japan on July 10-12, 2018, for further examination.

The unit was backflushed, and a quantity of debris was captured by the rig filter consisted mainly of paint and airplane ‘build’ material (Photo 33).

The unit passed a pressure drop test and fluid leakage check; however, it did not pass a functional check of the fuel filter bypass valve. The measured bypass valve ‘crack open’ pressure was approximately 8 pounds per square inch (psi) compared to the required CMM target of 24-26 psi. A low bypass crack-open pressure could result in chattering or premature operation of the bypass valve resulting in (a) unfiltered fuel entering the fuel system during normal operation (b) Accelerated valve seat wear which is currently being accepted as ‘normal’. Disassembly of the bypass valve found the valve conical sealing face to have minor contact wear which the vendor considered the to be normal for a unit with approximately 12,000 hours of service.

D.4.8 Main (LP & HP) Fuel Pump Assembly

The main fuel pump on the Trent 700 series of engine is a combined LP and HP pump from a single drive off the rear of the engine's external gearbox. The LP pump has a single stage centrifugal impeller that receives fuel from the aircraft wing tanks and delivers fuel to the FOHE and LP filter. The HP pump is a positive displacement spur gear type pump fitted with a fuel flow relief valve to prevent over pressurizing the pump casing.

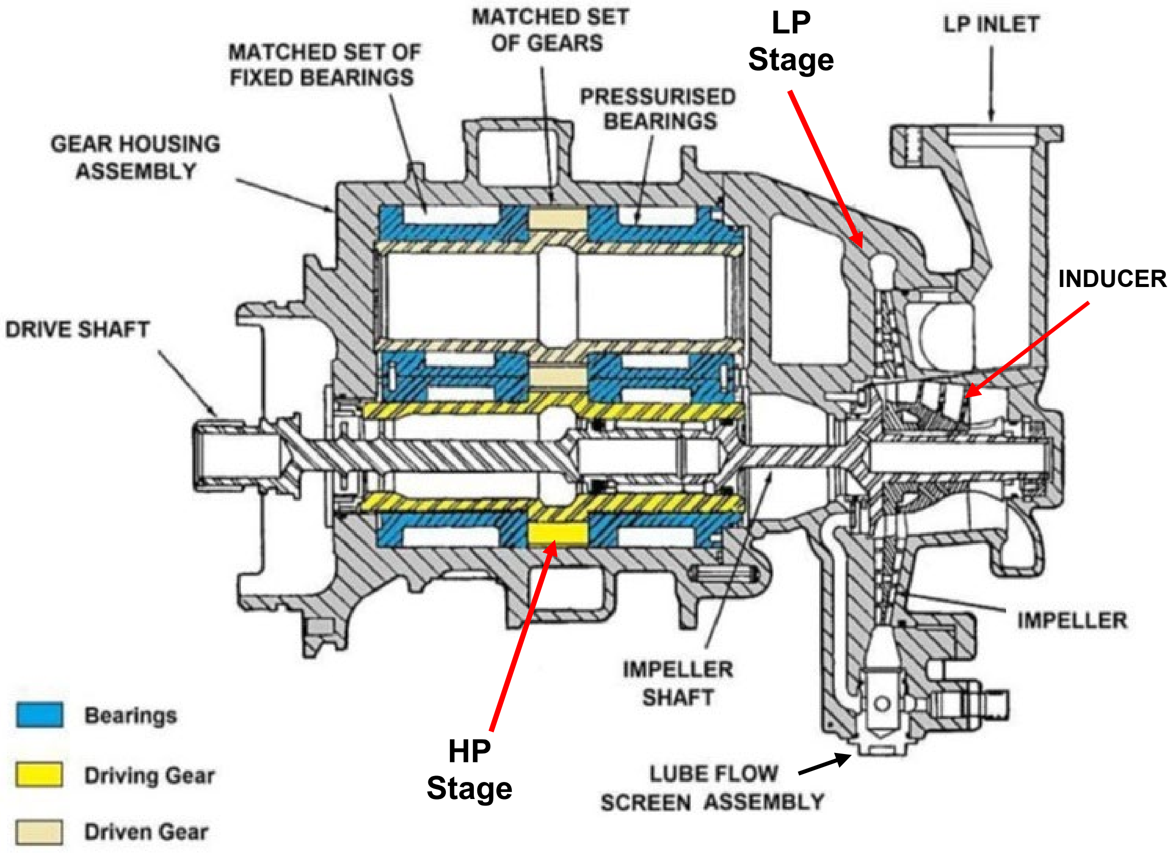


Figure 10 – Fuel Pump (LP & HP) Schematic

The HP pump receives LP fuel from the LP filter and delivers it to the FMU and VSV system and is mounted to the pump casing. The HP pump consists of driving and driven spur gears, which rotate within two leaded bronze fixed bearing sets. The pump assembly utilizes system fuel to lubricate and cool the pump during operation.

The fuel pump assembly, P/N 721400-3, S/N 2056 was the original unit fitted to the event engine since entry-into-service and had accumulated 11,879 hours TSN and 1,945 CSN. It was shipped to the manufacturer, Eaton (Argo-Tech Corporation) in Cleveland, Ohio where it was disassembled and examined on February 14-15, 2018.

No external damage to the pump assembly was observed. The gearbox interface of the pump exhibited no abnormalities or debris. The main shaft spline was undamaged, and the main drive shaft was match-marked to the housing. A breakaway torque of 100 inch-pounds was measured and as the shaft was rotated a running torque of 80 inch-pounds was measured, both normal values in Eaton experience.

D.4.8.1 LP Stage

A portion of the fuel flow in the LP pump is used to lubricate the boost stage bearings and is also sent to the drains tank ejector (DTE) and for lubrication of flows from the boost stage discharge through a lube flow screen (45µ). The layered lube flow screen consists of a facing screen, a backing screen, a drainage screen and backing plate. Debris on the screen is representative of fuel entering the pump. The lube flow screen (Ref. Figure 1) was partially clogged with debris (Photo 34) that, according to Eaton, were within the vendor's experience of overhauling typical service run fuel pumps.

Scoring was observed on the low-pressure pump stage inlet housing. A leading edge of the inducer vane exhibited an impact mark. Minor impact marks to the impeller were observed; however, all the marks were within the Eaton's experience of overhauling typical service run fuel pumps.

D.4.8.2 HP Stage

The discharge screen or HP wash flow filter – 70µ (Ref. Figure 6) was stained brownish-gold in color but free of debris (Photo 35).

The bare bronze surfaces of the fixed bearings were coked with black residue in noncontact areas (lands and spooled areas), which according to Eaton, was within the range of experience variation. Similar residue has been analyzed in the past and found to be fuel reaction product. Dry film at the faces and bores was generally intact and the bearing bores exhibited localized scoring wear at the inlet side.

Inspection of the fixed bearing set (Ref. Figure 10) noted cavitation damage to the discharge side of all four bearing faces (Photo 36) and bearing dams (Photo 37), which, according to Eaton, was abnormal. The pump housing material is anodized aluminum, and the gear housing bores were stained golden brown in non-contact areas. The dry film on the faces and bores was generally intact except for localized wear. The fuel discharge windows of the gear housing bores exhibited abnormal cavitation erosion wear (Photo 38). According to Eaton, cavitation at these locations occurs during pump operation at low inlet pressure to the gear stage, a condition that exists when there is insufficient fuel filling. Low inlet pressure to the gear stage could be caused by upstream fuel system restrictions such as the FOHE, LP fuel filter, external actuators feeding the HP pump inlet.

Examination of the HP pump drive and driven gears found evidence of deep cavitation erosion to the tooth roots and drive flanks (Photo 39 & Photo 40). A material section taken through one of the deeper cavitation areas found pitting within the allowable CMM limitations (Photo 41). Eaton stated that the cavitation erosion observed in gear tooth flanks and bearing dams were within normal operational experience for approximately 12,000-hour service life.

A material micro-section taken through two gear teeth and subsequent material analysis found the gears met the vendor material specification for case depth, case hardness, core hardness, and material composition. An SEM EDX analysis of the gear material found the composition comprised of Fe 82%, V 10%, Cr 6%, and Mo 1.3% which was consistent with the specified material. The composition of the gear and bearings closely matched the debris analyzed in the downstream VSV filters. The extent of the cavitation damage would indicate the gears were the probable source for material released into the fuel system.

The unusual cavitation wear in the fuel pump is another unusual finding, which could be a result of low inlet fuel flow caused by upstream blockage (possible FOHE) or fuel contamination. SEM analysis of the debris found in the VSVC and FMU filters showed agglomerations of very fine debris particulates blocking the filter elements, and consistent with pump wear and fuel breakdown products. Ordinarily this fine material should pass easily through the filters (MIF measuring 45µ and the Torque Motor supply filters measuring 80µ). However, there appears to be a process in which the material clumps together, possibly using the fuel breakdown products as a binder.

D.4.9 High pressure (HP) fuel filter

The pre-fuel nozzle HP fuel filter (See Figure 6) was removed from the pre-burner rail with no difficulty, and it appeared to be clean.

D.4.10 Fuel

D.4.10.1 Fueling History of the Event Airplane

According to HAL, no service activity related to the engine fuel system of the airplane was done during the 10 days it was in PAE undergoing cabin upgrades.

The fuel quantity of the A330 is 139,090 liters (36,744 US gallons) volume, equivalent to 109,185 kilograms (240,712 pounds) weight.

Record of the fuel quantities on the airplane during the time at PAE are given in Figure 11.

Aircraft	Date Arrived PAE	Date Departed PAE	Days Idle at PAE	Quantity of Fuel in Tanks While at PAE	Quantity of Fuel Downloaded at PAE	Quantity of Fuel Uploaded at PAE	Quantity of Fuel Load Departing PAE
N375HA	10/27/17	11/7/17	11	16,200 LBS	0.0 LBS	4,300 LBS	20,500 LBS

Figure 11 - Record of the Fuel Quantities on the Event Flight

HAL stated that they do not provide their own ground service at PAE and that the interior upgrade and ground service tasks were subcontracted to Delta Airlines and the Hawaiian and Delta task management systems were not easily compared. Despite multiple requests, limited fuel management information was available. The fuel management records were therefore not considered very reliable.

Of the records available, during the time at PAE the outboard tanks were left empty which limited proper sumping. On November 3, 2017, 4 days before the event flight, records indicate that sumping of the tanks was scheduled; however, it was not accomplished because the fuel temperature was below 4°C, too low according to the Airbus manual. The low ambient temperatures precluded sumping on at least two occasions. HAL was not able to confirm that that water drains were cleared on the event aircraft prior to their departures from PAE.

According to HAL, the Task Card allows for a minimum fuel of 15K lbs. if there is not sufficient time to preload the aircraft with 60K lbs. and allow 1 hour for settling. 60K lbs. is standard to ensure all tanks have a minimum of 10% of its capacity for gravity sumping. If 15K lbs. is used, the outer wing tanks may have fuel/water below the drain that is only sumped by the suction method.

It is likely that significant water was present in the system during the flight from PAE.

After the event, HAL initiated a review and revision of their fuel preload procedures.

D.4.10.2 Fuel Quality

A sample of Jet A were taken from Castle and Cook Aviation, truck 7, which was the truck that last fueled the event airplane, on 2017-11-17. The particulate test determined 0.55 mg/l, within the fuel specification limit. It also passed a thermal stability test at 260°C.

HAL took fuel samples from (Figure 12) the LH #1, #2, #3 and #4 inner tanks and the RH #5 outer tank, RH #6 surge tank, RH #1, #2, #3 and #4 inner tanks on February 9, 2018 and sent to Inspectorate America Corporation fuel laboratory in Ferndale, Washington for microbial contamination evaluation.

The findings from the lab revealed that the:

- The "particulate contamination" was in the normal range for ppm.
- The fungi quantity in the LH #3 inner tank was 10,000 per milli-liter – considered heavy
- The fungi quantity in the #6 RH surge tank was 1000 per milli-liter - considered moderate

Results from this analysis were inconclusive. Although some fungus contamination was found in the fuel, no fungal contamination was found in the fuel system components that were examined.

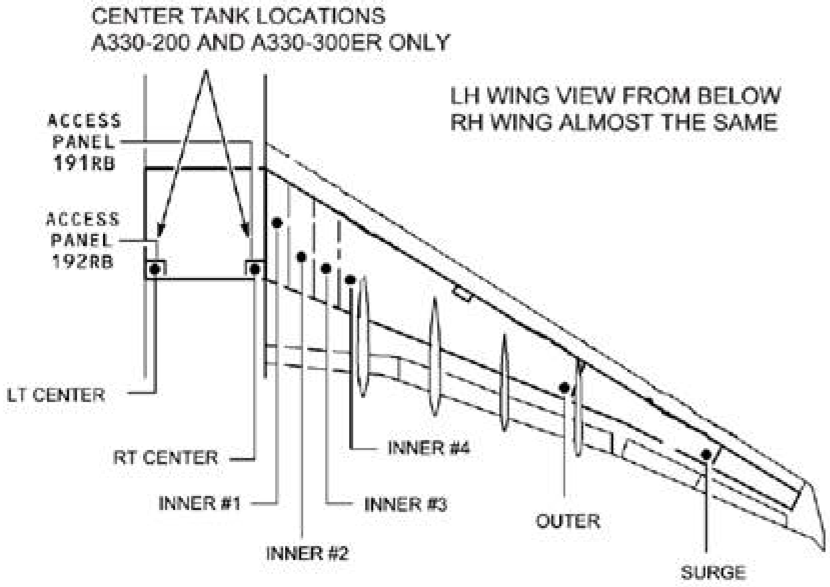


Figure 12 – Airbus 330 Wing Tank Schematic

Bulk fuel samples taken from the event airplane were sent to Rolls-Royce Fuel and Lubricant Laboratory, Derby, UK for evaluation and analysis including fuel thermal stability testing and were completed with no evidence of degradation found.

A sample was taken from the LP fuel system of the engine before it was examined at the N3EOS facility in Germany. Additionally, during the engine examination at the N3EOS facility in Germany fuel samples from several locations of the fuel system including the VSV controller and actuator tubes. The samples were visually examined after the draining, and a small amount of fine shiny flakes as well as fine dark soft, elastomeric material, consistent with a polymer, were noted from the following sample locations: The tube between the LP filter and the HP inlet, the LP fuel filter housing, the FMU, LP fuel pump.

A filtration test highlighted the presence of particulate. It failed a thermal stability test at 260°C with a tube rating of less than 4P. The industry standard jet fuel specify that a fuel must have a tube rating of less than 3P (<3P) at 260°C. 'P' refers to a visual peacock effect of the deposits. The lab stated that the sample was likely to have passed at the 245°C. The Trent 700 certification specifications permitted a re-test at 245°C, for those failing at 260°C.

According to R-R experience, fuel subjected to elevated temperatures on marginal stability fuel, would require a number of hours to see detectable differences in valve behavior such as stiction or hysteresis. Additionally, no significant fuel lacquering was noted during the disassembly of the fuel system components. It is unlikely that the fuel component had a large influence on the clogging of the filters.

The possibility of microbial contamination was considered but ultimately discounted because (a) microbial contamination typically shows itself as biofilms and deposits in other areas of the fuel system and blocks filters - this condition was not found. (b) the FOHE end face looked clean from a microbial perspective (c) the SEM EDX analysis of the TM indicated that deposits were from fuel breakdown components, and (d) ay review and comparison of detailed images from experience of biological contamination from another airline operator concluded that the deposits on fuel wetted surfaces of the event system did not look similar regarding the water-soluble microbial deposits seen in their fuel systems.

D.4.10.3 Evaluation of Water-Soluble Components in Fuel

The presence of aluminum sulfate (alum) throughout the LH engine fuel system is unique to this event. Alum is used in the water treatment industry to coagulate contaminants and thus aid their removal. It is also used in the paper manufacturing industry. Alum is not used in the airplane industry. There is evidence that alum dissolved in water can produce sulfuric acid that may chemically attack components (Ref. Photo 25 & Photo 26) and may strip the lacquer off fuel pipes and valves.

The NTSB has found some aviation industry reports that have observed dissolved sulphate in water can act as a binding agent leaving water soluble residues in the locations of screens and filters resulting in a binding attraction from an ionic behavior. The adhered agglomerations observed in the VSV TM SP filter was a possible result of sulfate action.

D.4.10.4 R-R Test of Hypothesis of Water-Soluble Scrub of Contaminants in MIF

As discussed in the paragraph 'D.4.5.5 The Main Inlet Filter (MIF)', the VSV TM can operate normally with a 95% blockage of the TM filters and the EEC will pick up a gradually slowing behavior of VSV TM and trigger a maintenance action at about 97-98% blockage, so the sudden blockage of the filter with a 95% blockage cannot be explained. Another abnormal finding was the cleanliness of the MIF which was inconsistent with its time in service.

To reconcile these two abnormal observations, R-R developed a hypothesis that the MIF had accumulated water-soluble residues that were suddenly released when an amount of water containing alum was passed through the filter, quickly cleaning it, and causing a cloud of debris to flow to the VSV TM SP filter, clogging it.

R-R initiated a study by collecting several high-time MIF filters from operational VSV controller units that had been sent to the UTAS factory for overhaul. Half the MIFs were then subjected to two different methods of debris extraction:

- The first consisted of placing the MIF into a solvent for 10 minutes with ultrasonic agitation, as per standard process clean, followed by a 2-minute water immersion followed by a 1-minute ultrasonic agitation. The released debris was captured by a laboratory filter after each process and compared.
- The second consisted of placing the MIF into a solvent for 10 minutes with ultrasonic agitation, as per standard process clean, followed by a 24-hour water immersion followed by a 1-minute ultrasonic agitation. The released debris was captured by a laboratory filter after each process and compared.

The other half of the MIFs were subjected to two other methods of debris extraction:

- The first consisted of placing half of the MIF filters into an aluminum sulfate solution for 2 minutes with by 1-minute ultrasonic agitation followed by a 10-minute ultrasonic agitation in a solvent as per standard process clean. The released debris was captured by a laboratory filter after each process and compared.
- The other half of the filters were placing into an aluminum sulfate solution for 24 hours followed by 1-minute ultrasonic agitation followed by a 10-minute ultrasonic agitation in a solvent as per standard process clean. The released debris was captured by a laboratory filter after each process and compared.

Images of the captured debris from the MIF is shown on Figure 13.

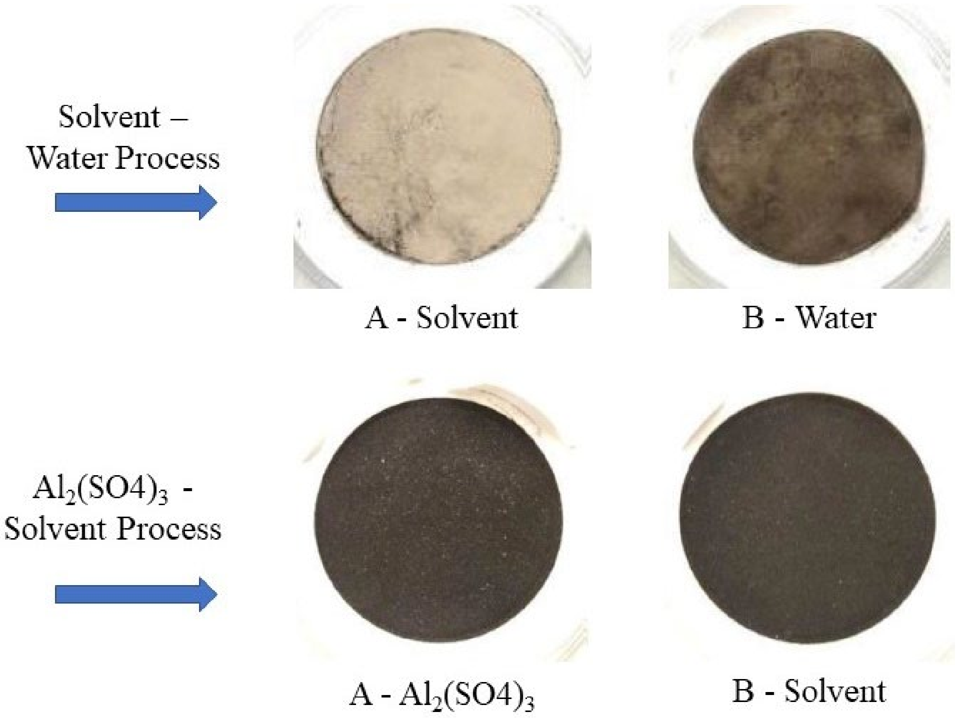


Figure 13 – Debris Captured from MIF After Immersions

After the filter tests, the water-soluble residue was extracted from the debris in the laboratory filters. After the water was evaporated, the quantity of the debris was measured. Those filters that were water soaked had between 11 and 18 mg of residue while those soaked in the $Al_2(SO4)_3$ (alum) solution had between 76 and 83 mg of residue.

Findings of the tests:

- Notably more deposits were evident from the post (alum) solution extractions.
- This mechanism is consistent with the event MIF releasing debris due to water exposure.
- Debris extraction tests indicated this water-soluble binder released significantly more material after the filter had been exposed to water.
- The test indicated exposure to both water and the alum solution resulted in some degree of cleaning, with the presence of alum having marginally more impact, likely because of the higher acidity.
- Laboratory findings confirmed that filter debris comprised of two distinct elements which were (a) metallic particulates (predominately wear products) and (b) fuel-based products in the form of particulates in a water-soluble binder.
- Comparative findings were demonstrated during assessment of the LP filters on the event aircraft.

Subsequent testing with various service-run filters has shown the same results indicating the debris binder is water soluble and is not adversely affected by solvent cleaning.

D.4.10.5 Airplane Water Management

On the Airbus A330-200, fuel is supplied to the engines from the aircraft inner tanks via two main fuel pumps in the left wing and two main fuel pumps in the right wing. The pumps are located within a collector cell to ensure their immersion in fuel during normal operation.

Aviation fuel is hygroscopic and will therefore absorb water from the air. Fuel uplifted in warmer, more humid airports will have a greater amount of dissolved water, despite efforts by the fuel suppliers to remove free water from the supply. The other source of water occurs when the aircraft descends through humid warm air, which enters the tank through the vents. As warmer humid air hits the cold aircraft structure, water condenses on the surfaces.

The HAL A330 fleet incorporate an additional water management system in the form of jet pumps. During fuel pump operation, the jet pumps draw fuel from the low points in the tank and continuously mix any residual water into the fuel to disperse it. This results in the removal of a large proportion of settled water.

If an aircraft is not operated for several days, water begins to settle out and descends to the low points in the tank. To prevent water levels in the tanks increasing to a point affecting aircraft operation, regularly water draining or “sumping” must be undertaken in accordance with Maintenance planning document (MPD) Task 281100-08.

Review of the water management history for aircraft N375HA indicated that no water sumping had been performed following the modification work at PAE. HAL maintenance records indicated that the last aircraft sumping had been completed on October 22, 2017, at which time the fuel tanks were found to be free of water.

The event aircraft had been on the ground for 10 days undergoing cabin modification prior to the incident. Fuel supplier Castle and Cook Aviation uplifted 4300 lbs. of fuel approximately 1 hour prior to engine start, with departure fuel level reading 20500 lbs. HAL/Delta Airlines’ records from the October 27, 2017, indicate tank sumping could not be completed due to low fuel temperature (HAL task card prevent sumping below <5°C). The AMM does provide an alternative sumping method if fuel temperatures are below 5◦C; however, this was not applied. The AMM allows for additional fuel to be added, helping to increase the fuel temperature within the tanks’, provided fuel is allowed to settle for 1 hour before sampling.

Examination of the fuel components found significant evidence of water content in the fuel, supported by the presence of alum contamination.

Post event sampling records from the November 9, 2017 recorded 1.0 and 0.5 liters of water recovered from the left and right #3 tanks respectively. A review by HAL operations safety personnel identified several inconsistencies in the water management records, with many not containing information of fuel on board (FOB), temperature and method used.

D.4.10.6 West Coast Fuel Quality

The NTSB has become aware of other engine shutdowns, where further examination of the fuel related components found ammonium sulfate rich deposits as well as other water-soluble constituents. These airplanes have been operated predominantly in the United States west coast.

Another current study is looking into the fracking, and the methods used to chemically recover the oil. It is thought that many of these chemicals are water soluble and remain in the fuel even after the refining process. These contaminants are subsequently transferred through the fuel system and collect on the surfaces of the filter element. No clear results have yet been published.

HAL gets its fuel overwhelmingly from United States west coast. Nine of the events airplanes last 10 fueling locations were in Seattle-Tacoma International Airport (SEA), Paine Field Airport (PAE), Daniel K. Inouye International Airport (HNL) (5 times), Los Angeles International Airport (LAX), Harry Reid International Airport (LAS), Oakland International Airport (OAK), all in the west coast. The one exception was Incheon International Airport (ICN), Korea.

D.4.10.7 Other Investigations

During the investigation period, it was noted that other agencies were undertaking research into water-soluble deposits in engine components. The Coordinating Research Council (CRC), a non-profit organization that directs engineering and environmental studies, submitted a proposal on April 9, 2018 to undertake a new research project reference No. AV-25-16. The background to the research noted that several airlines had suffered disruptive incidents (such as aborted take-off, technical delays from engine start faults, etc.) over the preceding years. The incidents primarily occurred in North America and involved several airframe and engine types. The CRC research program sampled fuel from various airports around the USA over a 12-month period and the study is still ongoing at the time of this report issue.

One of the significant findings related to the discovery of water-soluble deposits on engine hardware that did not appear related to by-products of fuel thermal oxidation, such as water-insoluble fuel lacquering.

Photo 1 – Left Wing Damage

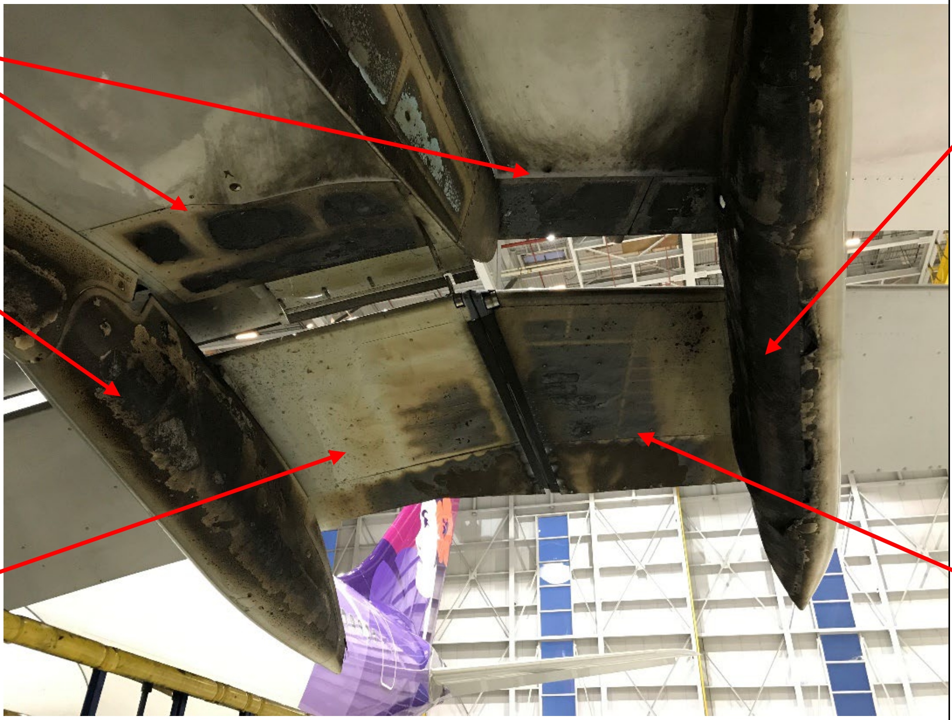


Photo 2 – Left Wing Damage

Photo 3 – Left-Side of Event Engine S/N 42543

Photo 4 - Front View of Fan

Photo 5 - Common Nozzle Assembly – Installed, Aft View

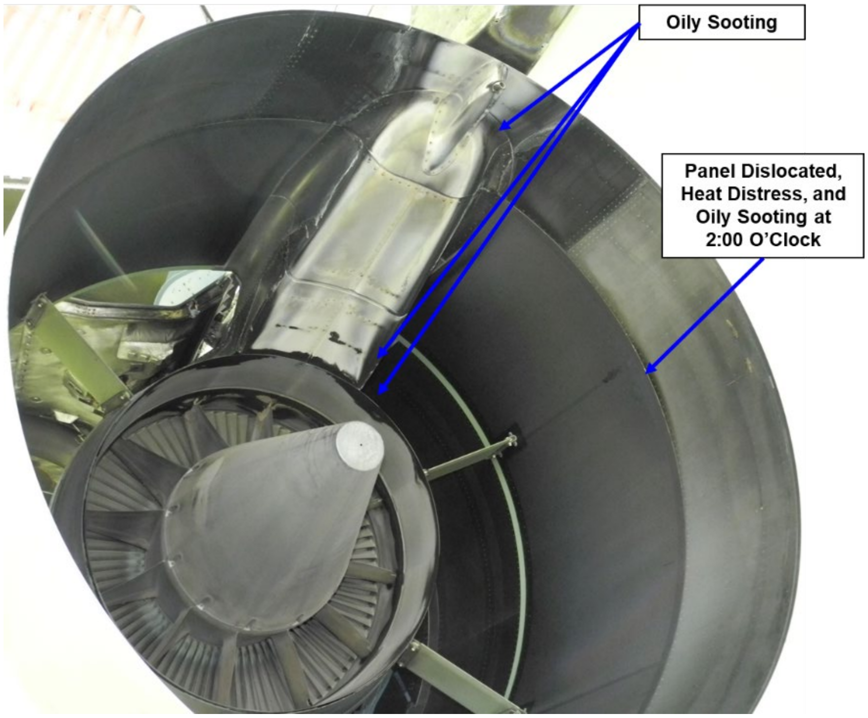


Photo 6 – VSV Actuator Ram Measurement

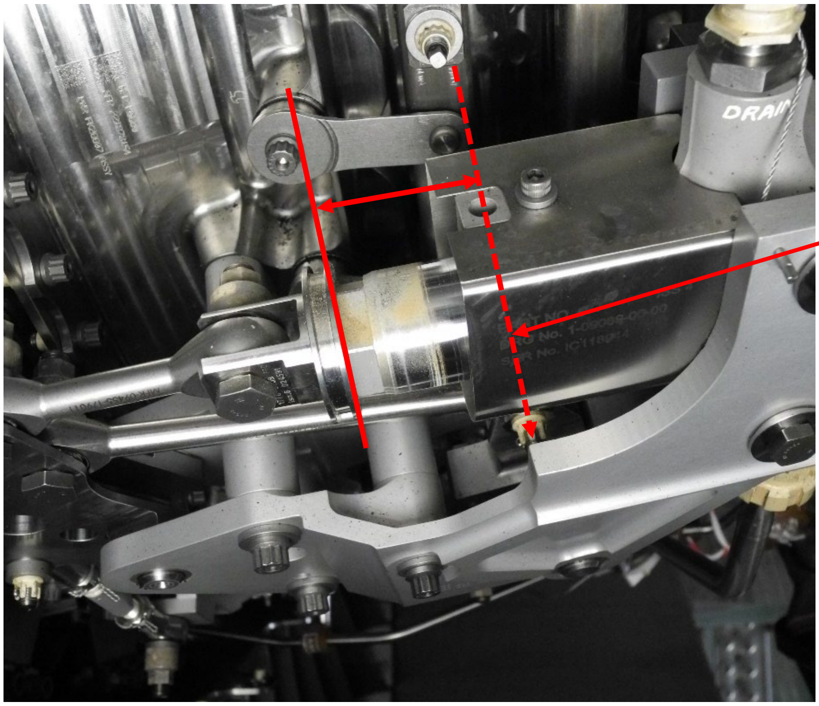


Photo 7 - Variable Stator Vane (VSV) Controller

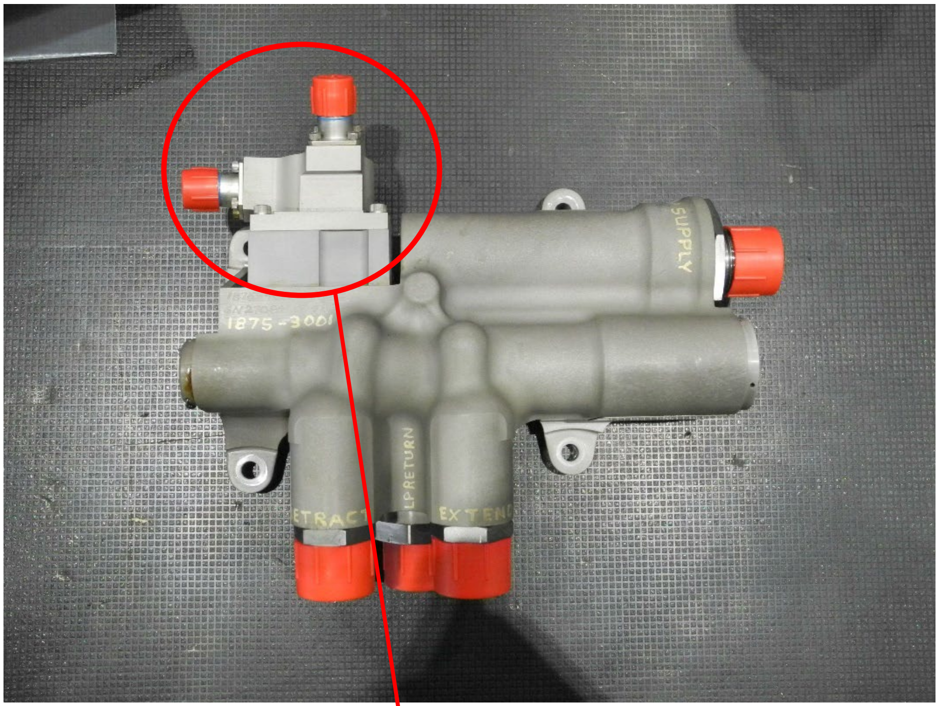


Photo 8 - Variable Stator Vane (VSV) Controller Torque Motor

Photo 9 - Left VSV Actuator – In Situ

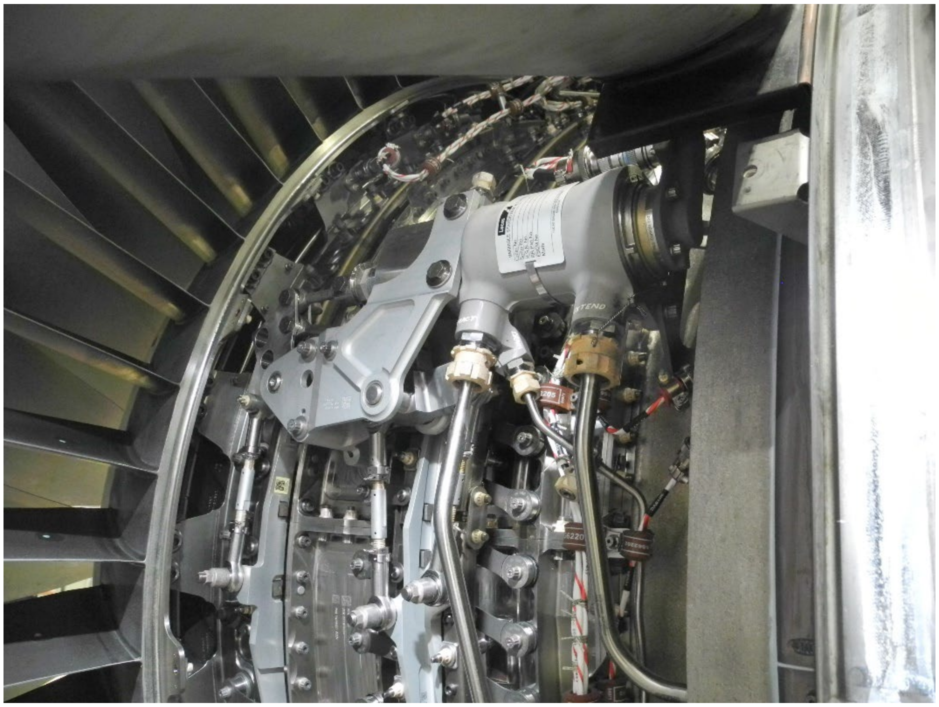


Photo 10 - VSV Actuator – Prepared for Shipping and CT Scan

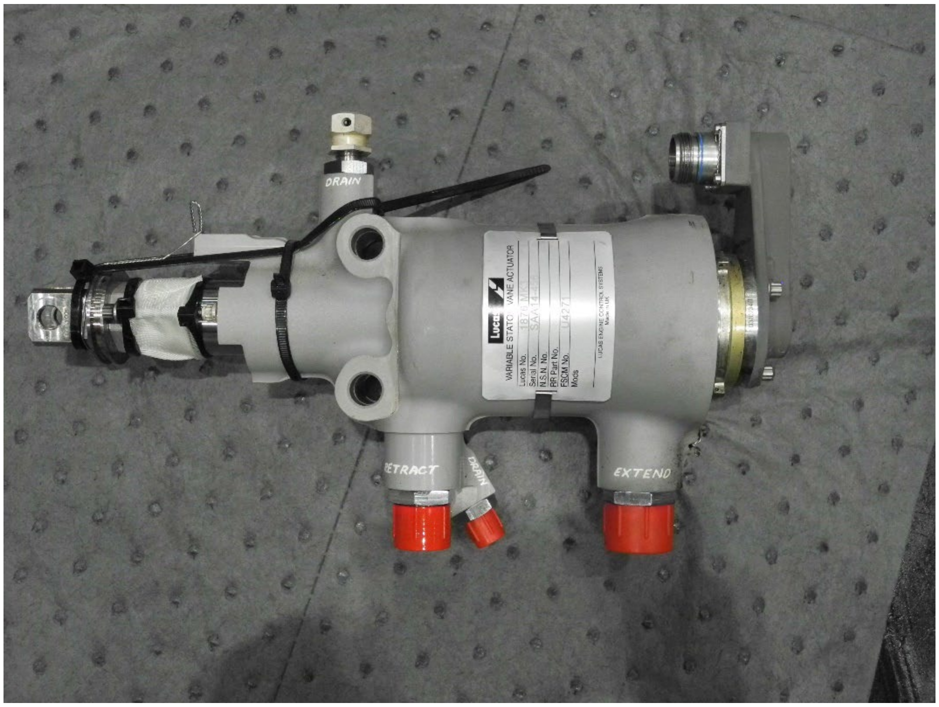
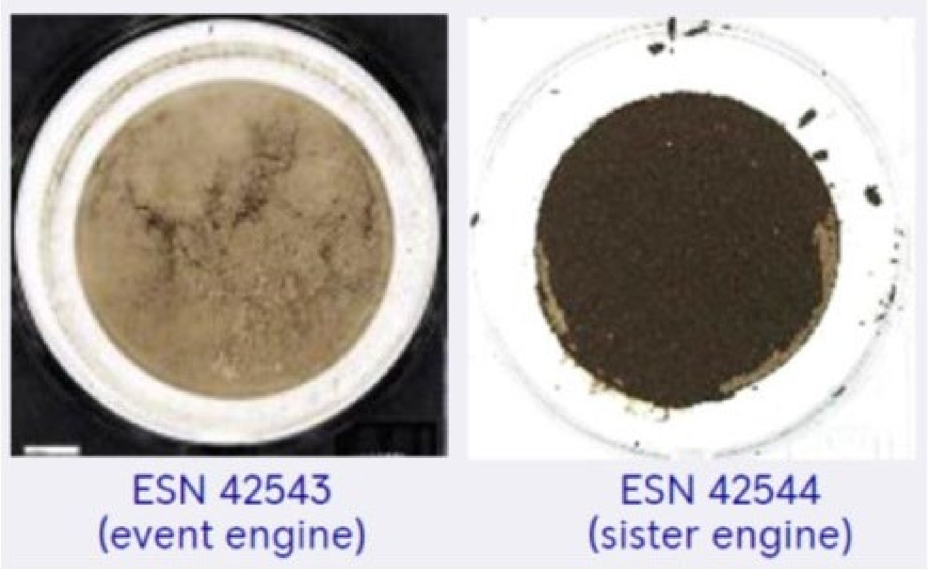


Photo 11 – Control Servo Valve (CSV)

Photo 12 – Event Engine MIF (45µ) – Remarkably Clean

Photo 13 - Laboratory Filters Containing Backflushed Debris From (45µ) HP Filter

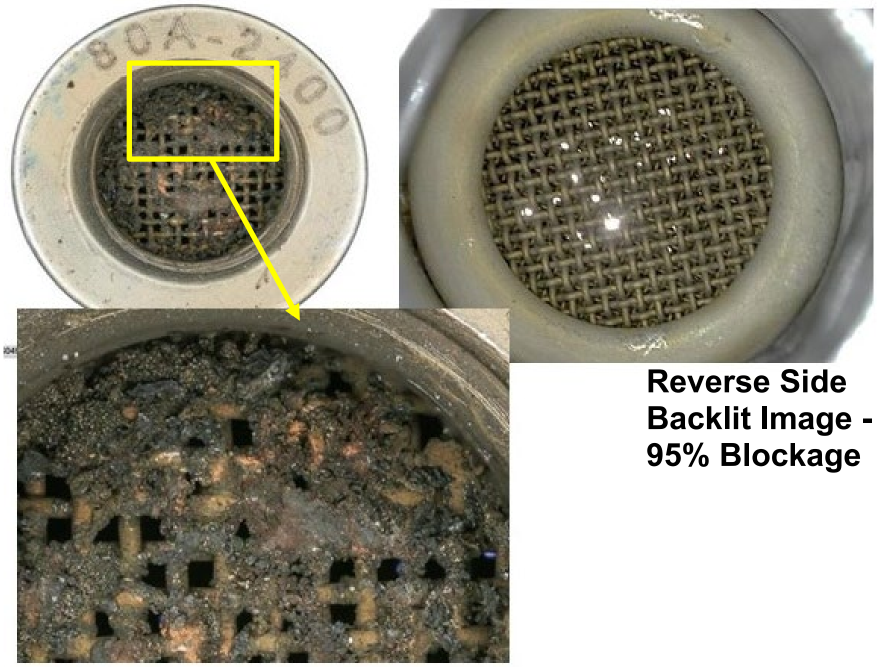


ESN 42543
(event engine)

ESN 42544
(sister engine)

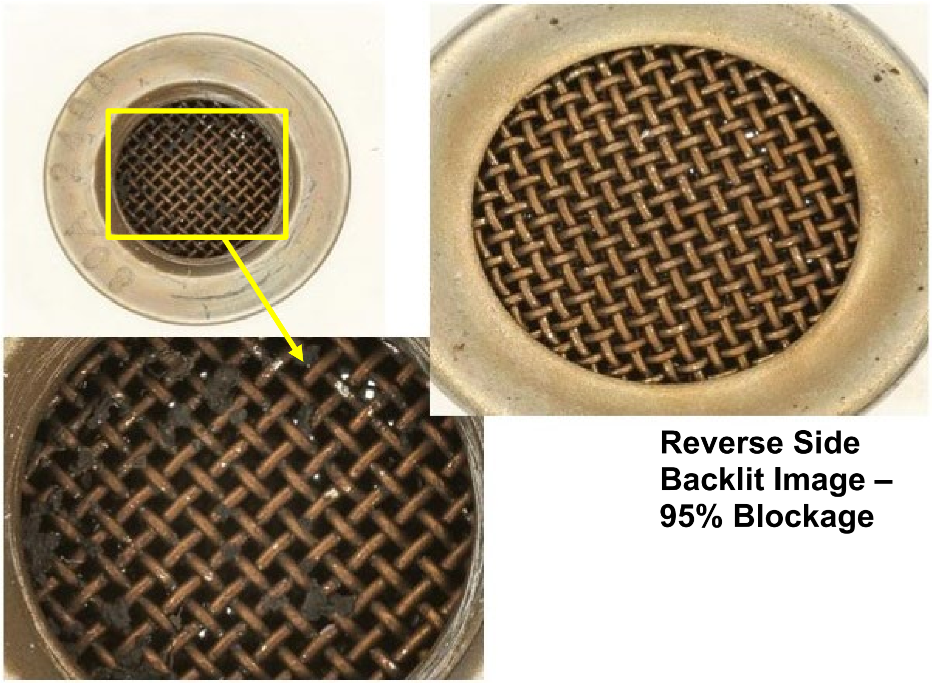
Photo 14 – Torque Motor Supply Port (70 - 80µ) Filter Element (wet)

Photo 15 – ESN 42543 TM Supply Port Filter (dry) – Lab Photos



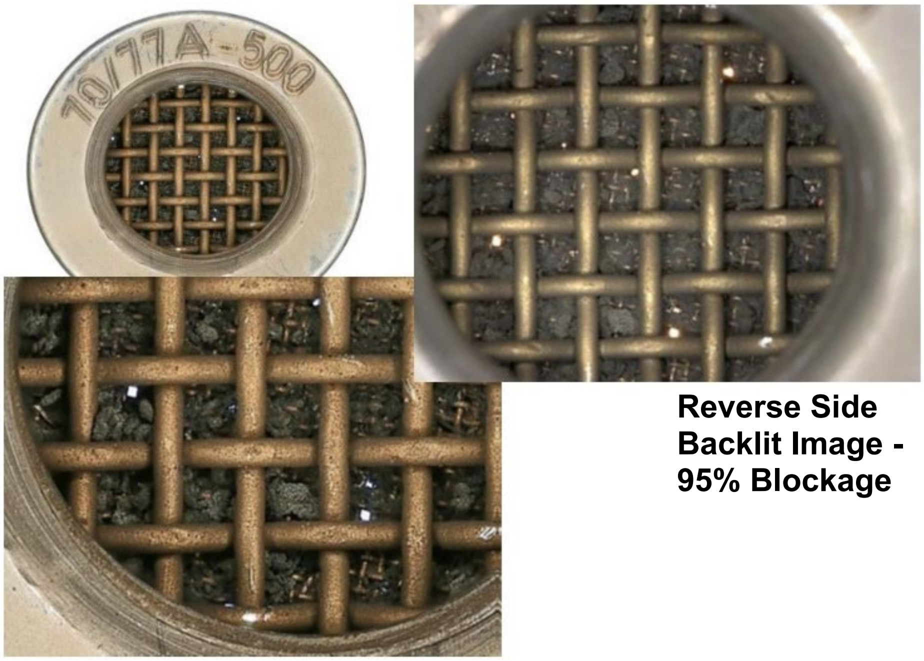
Reverse Side Backlit Image - 95% Blockage

Photo 16 - ESN 42544 TM Supply Port Filter (dry) – Lab Photos



Reverse Side Backlit Image – 95% Blockage

Photo 17 – ESN 42543 FMU FMV TM Supply Port Filter (dry)



Reverse Side Backlit Image - 95% Blockage

Photo 18 – C2 Nozzle Deposits on Flapper Valve Face

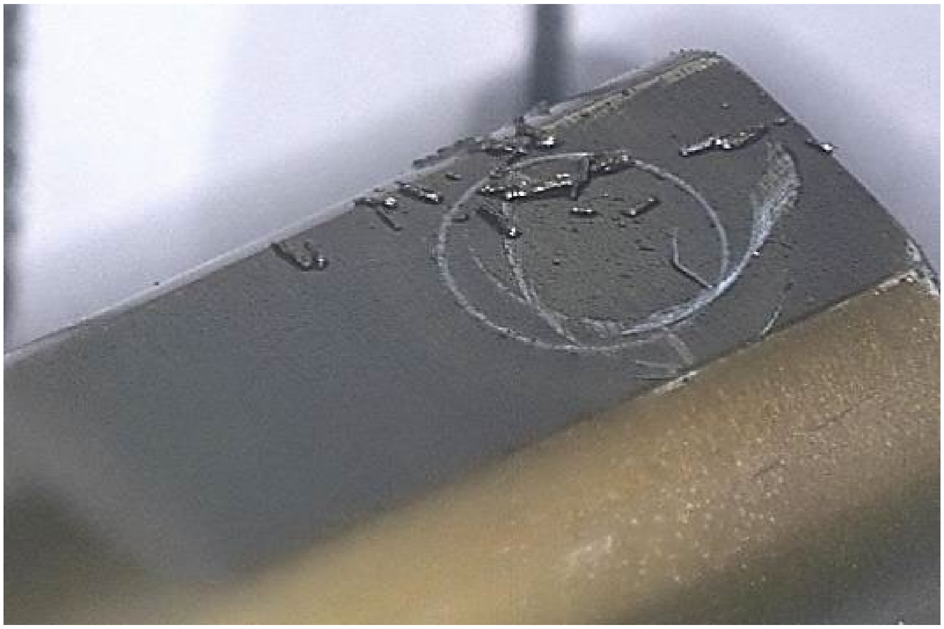
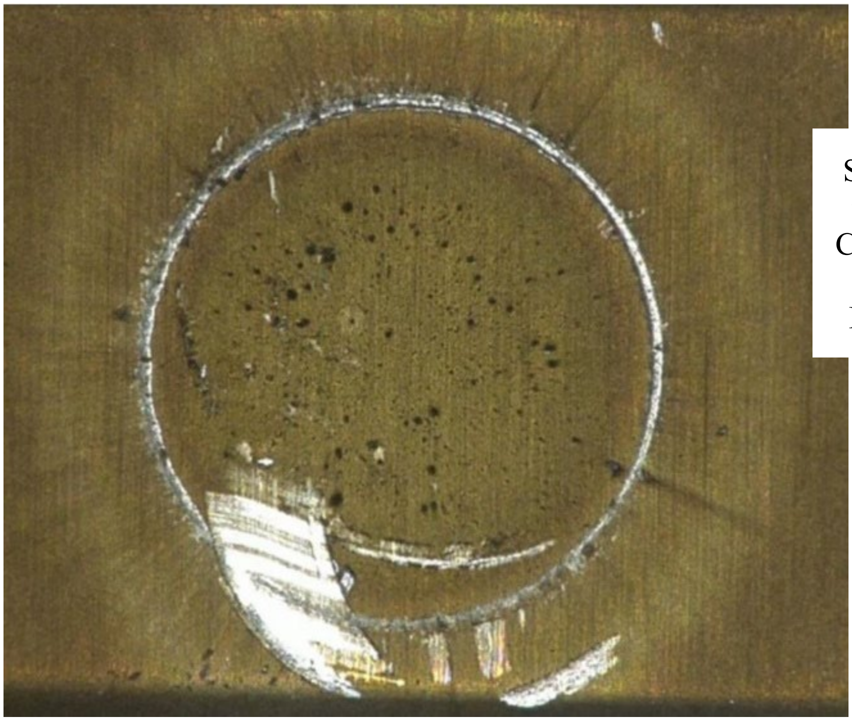
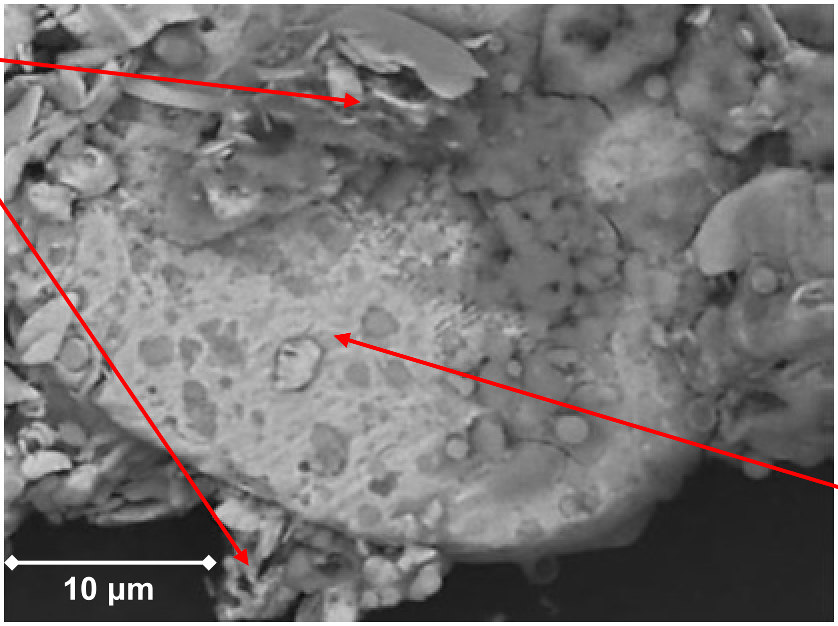


Photo 19 – Flapper Valve 'Sun Ray' Contact Marks with Nozzle



Sun Ray Pattern is Indicative of Contamination in Nozzle for Extended Time

Photo 20 – SEM Image of Flapper Valve Debris Showing Larger Particle with 'Agglomerated' Material



Agglomerated Material

Larger Particle – Non-Homogeneous

Photo 21 – VSV Actuator Disassembly

Photo 22 – Translucent Globular Deposits found on Internal Surfaces of LVDT Housing

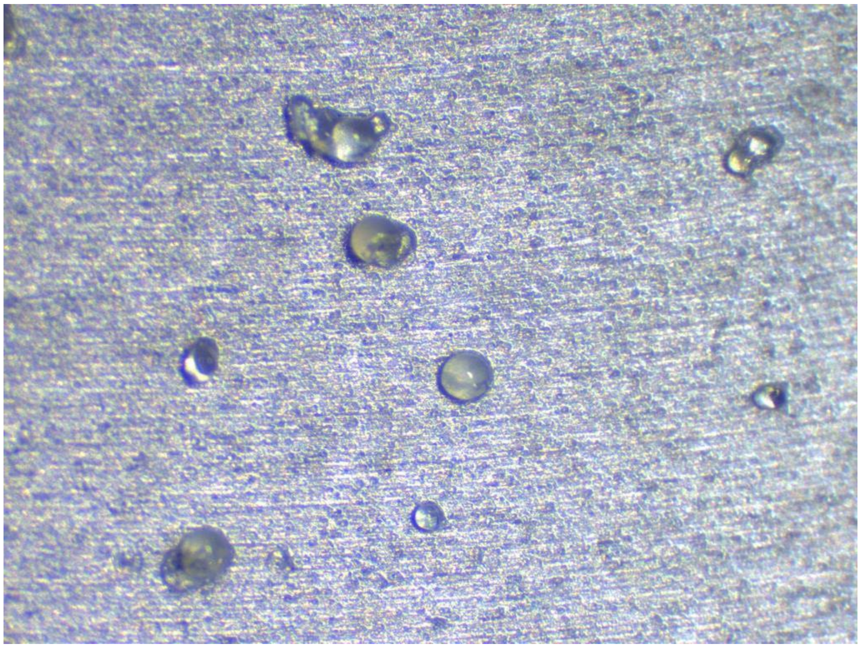


Photo 23 – VSV Actuator Piston - White, Dried Deposits

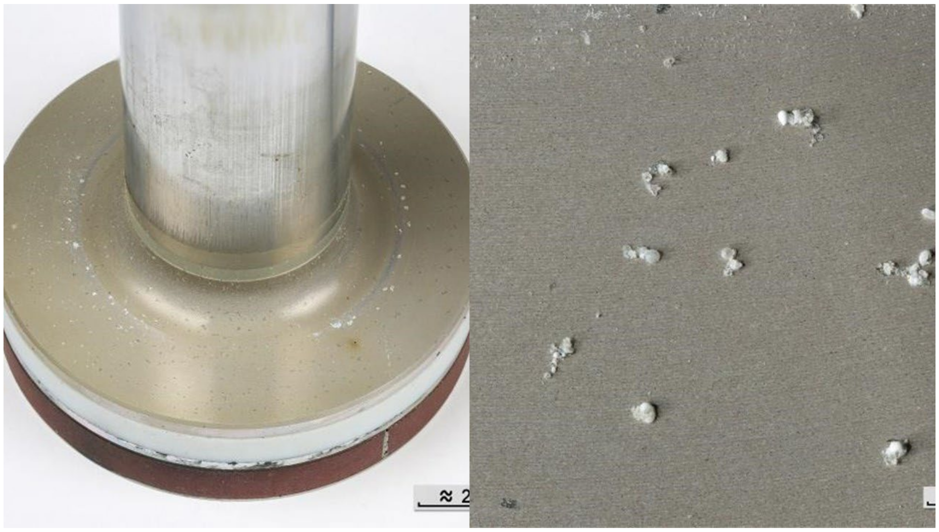


Photo 24 – VSV Actuator Piston - Aluminum Sulfate (Alum) Deposit

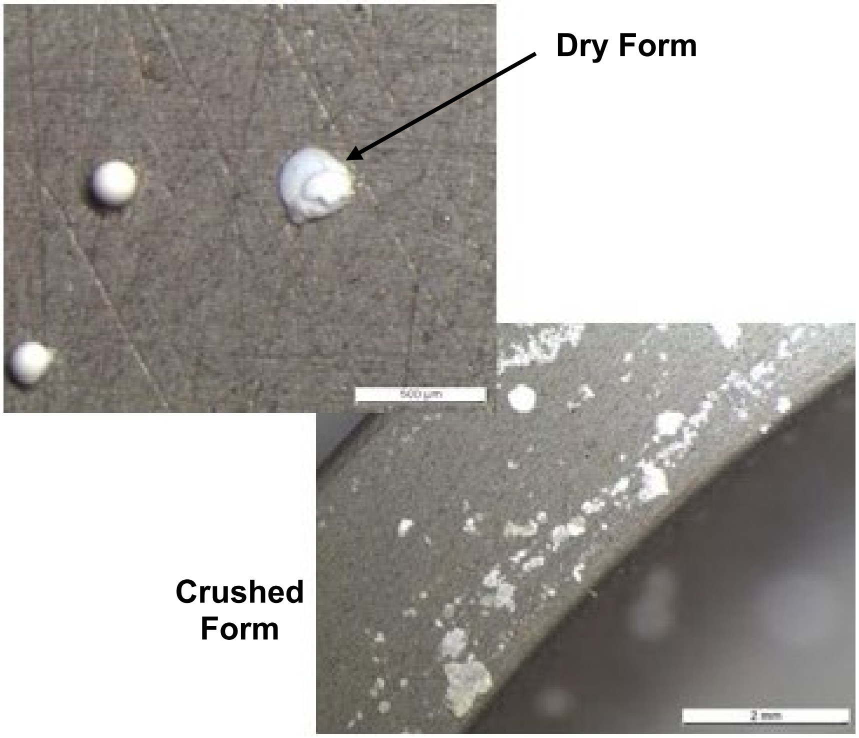


Photo 25 – VSV Actuator Piston Surface Corrosion

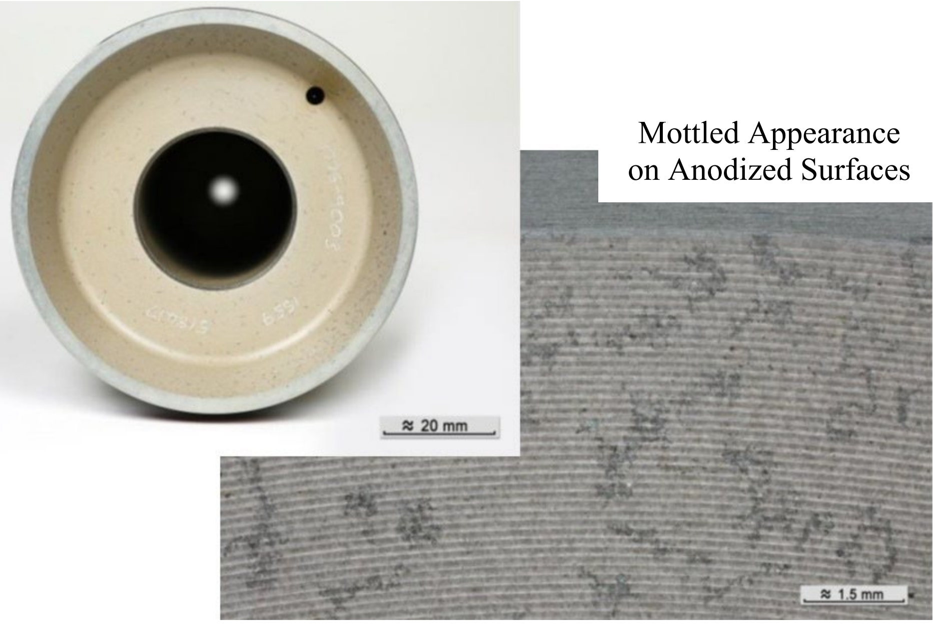

Mottled Appearance on Anodized Surfaces

Photo 26 – VSV Actuator Piston Surface Corrosion

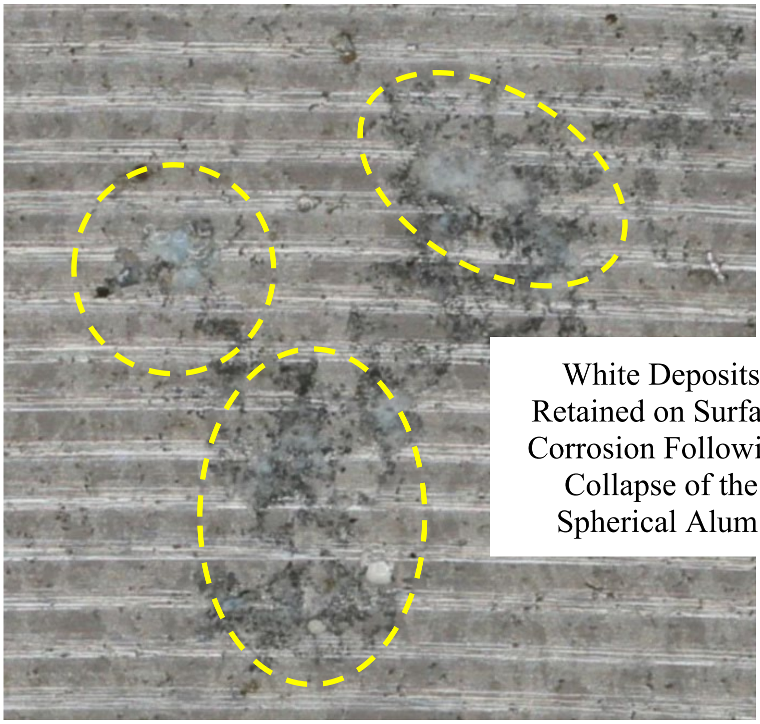

White Deposits Retained on Surface Corrosion Following Collapse of the Spherical Alum.

Photo 27 - LP Filter to HP Inlet Transfer Tube

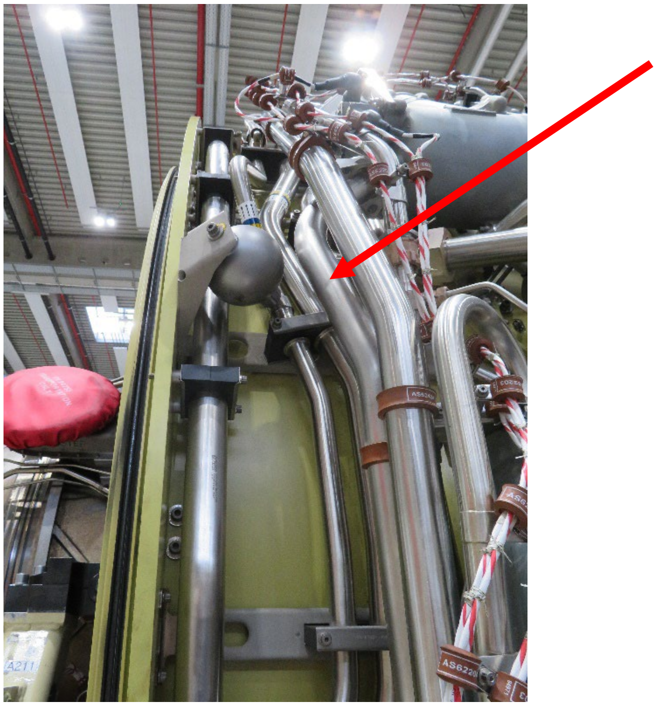
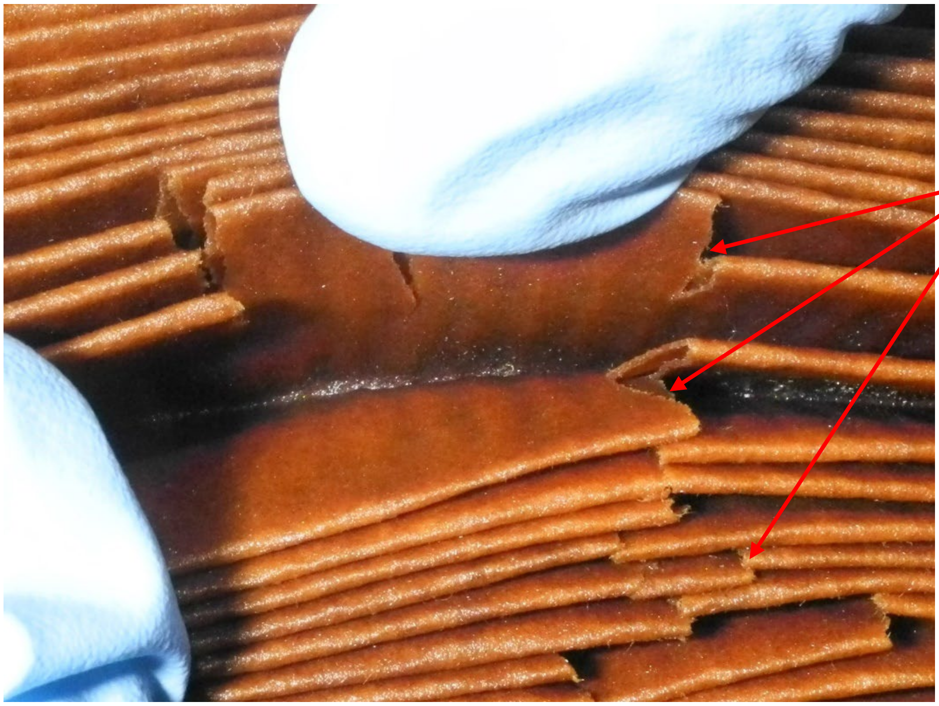


Photo 28 - LP Fuel Filter Element – Fine Metallic Debris in Pleats



Fractures in the Filter Media Occurred During Inspection.

Photo 29 – LP Fuel Filter – Visual & Chemical Analysis

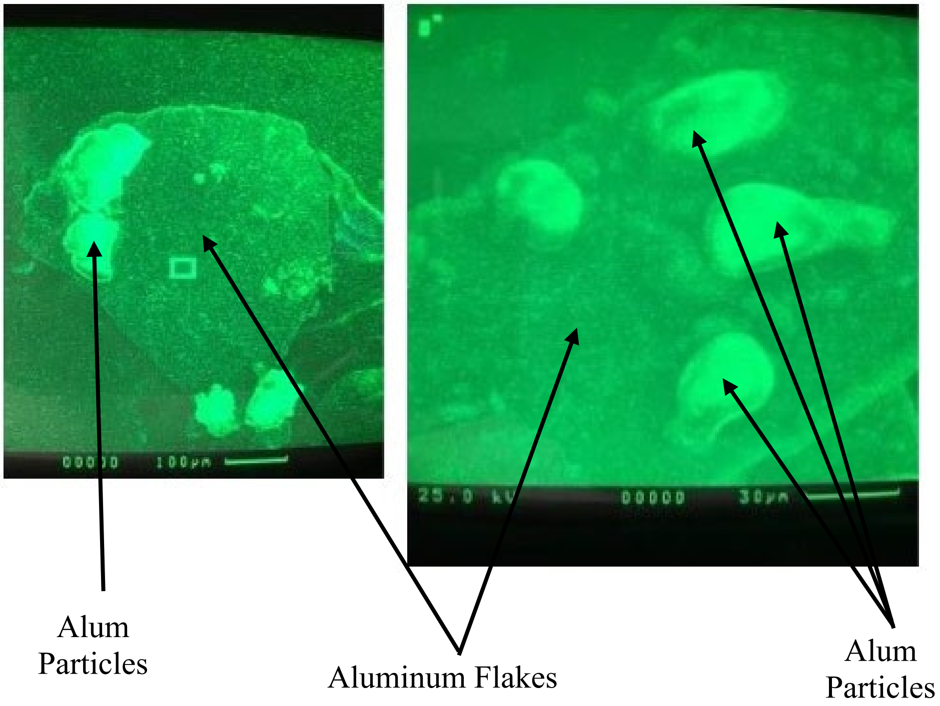


Photo 30 - Fuel Oil Heat Exchanger

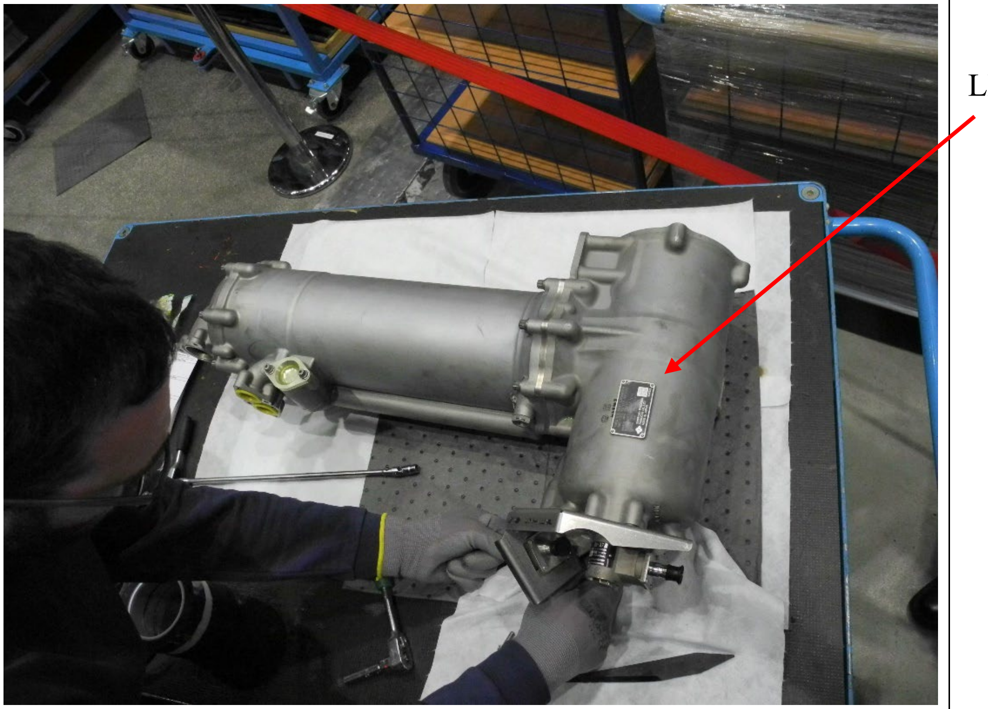
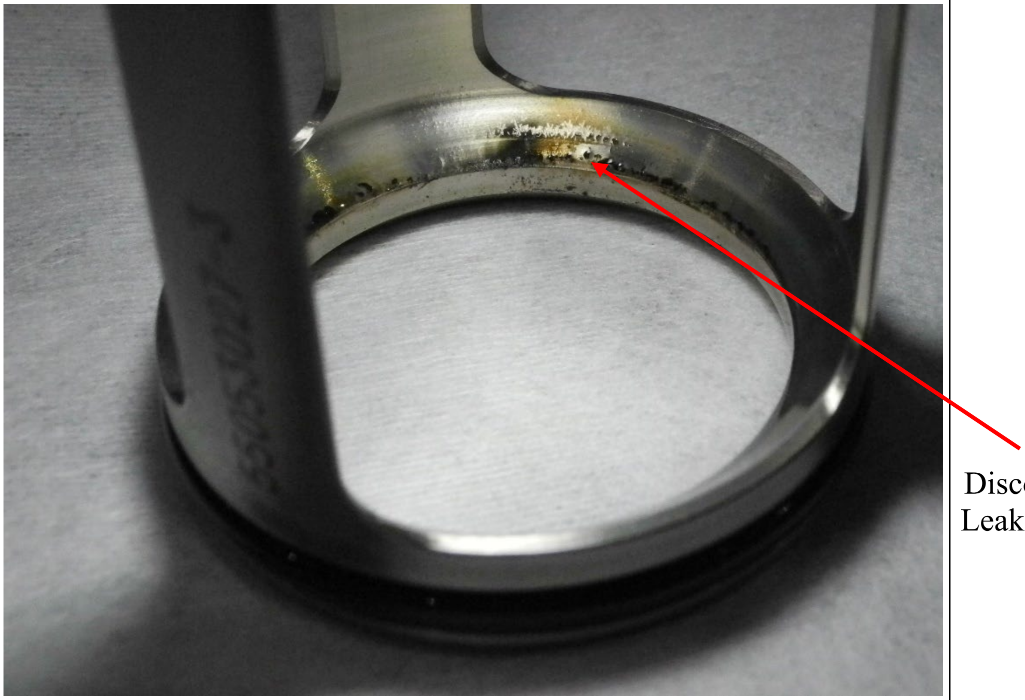
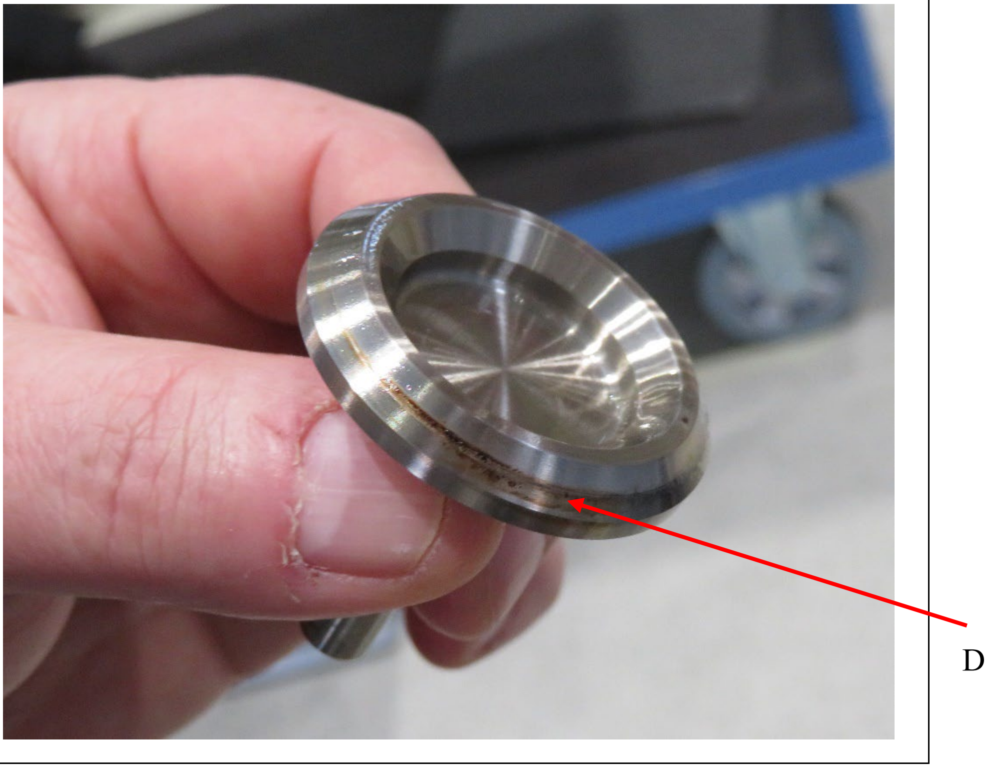


Photo 31 - Fuel Filter Bypass Valve – Valve Seat



Wear,
Discoloration and
Leakage Evidence

Photo 32 - Fuel Filter Bypass Valve – Conical Valve



Wear and
Discoloration

Photo 33 – FOHE Backflush Debris

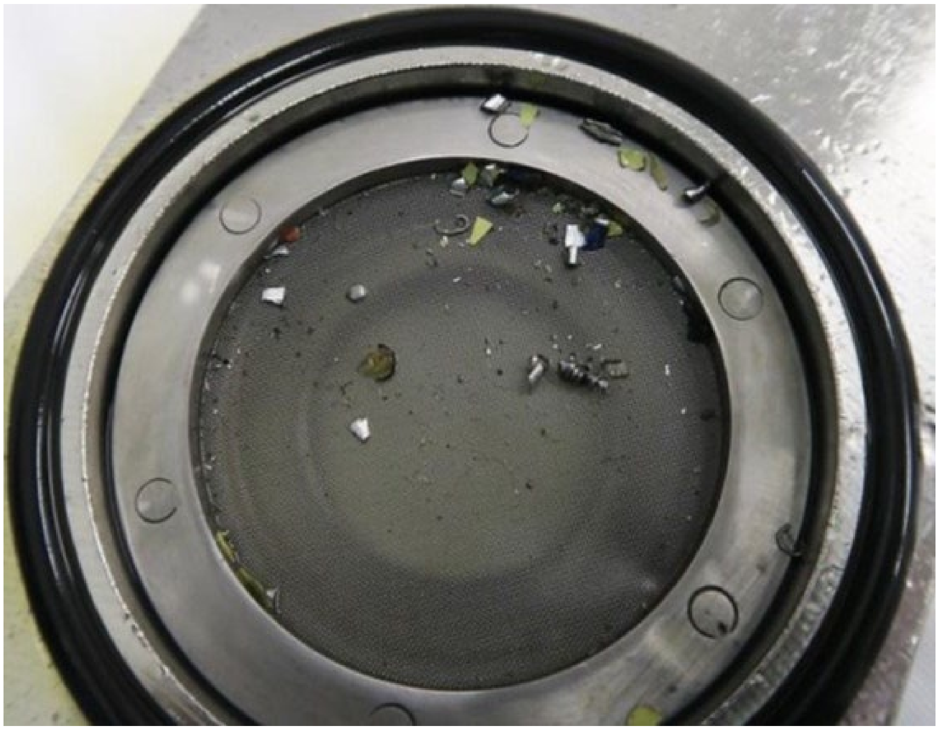


Photo 34 – Fuel Pump Lube Flow Screen – Partially Blocked

Photo 35 – Fuel Pump HP Wash Flow Filter

Photo 36 – Cavitation Erosion on Discharge Side of Fixed Bearing Face – Abnormal Wear

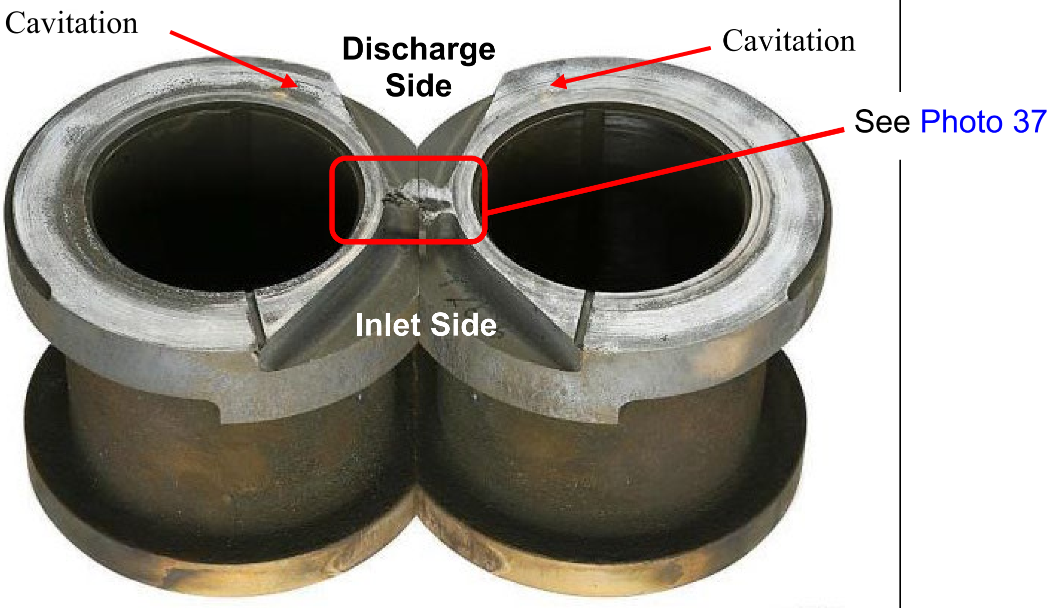


Photo 37 – Detail of Cavitation – Normal Wear

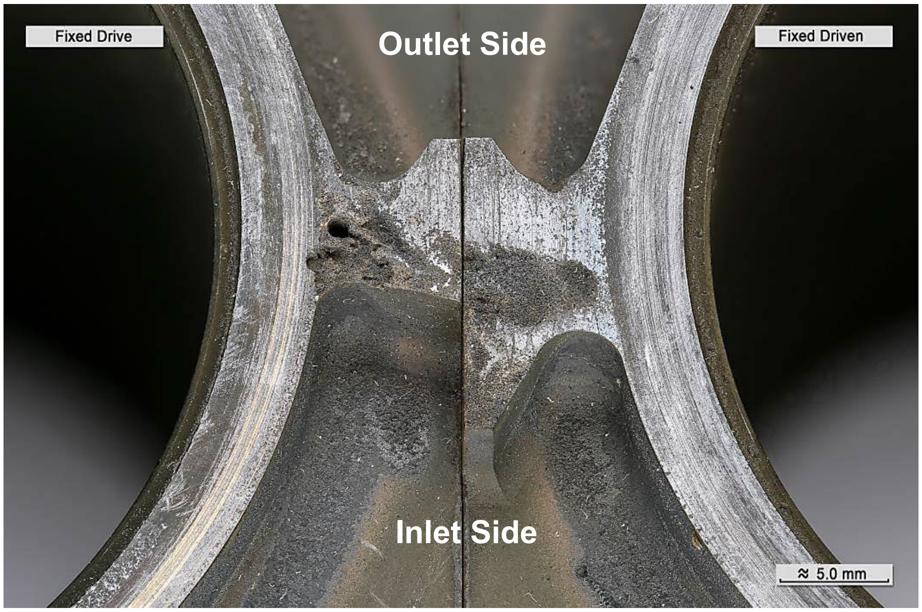


Photo 38 - Fuel Discharge Window of the Gear Housing Bores

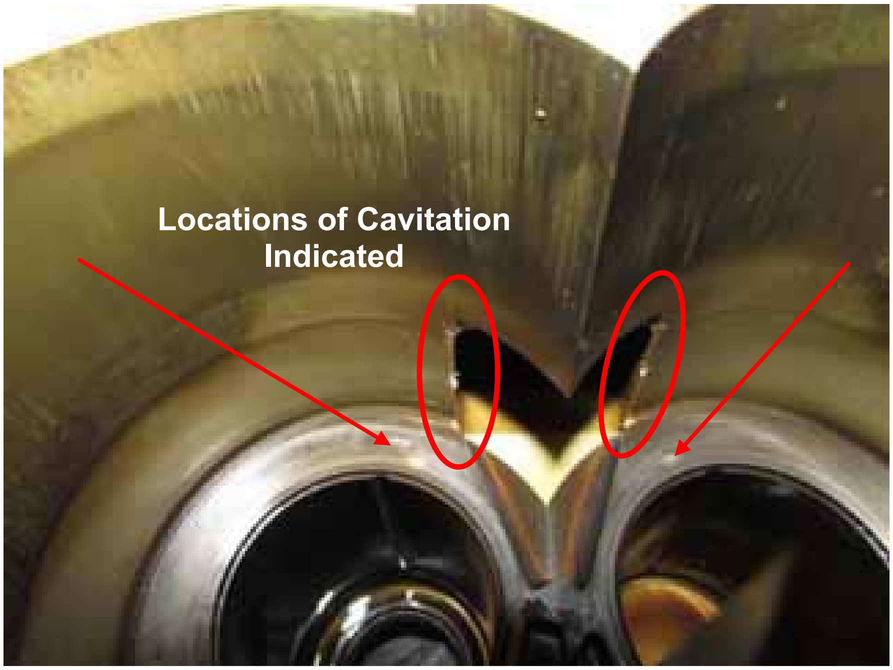


Photo 39 – HP Fuel Pump Drive Gear – Cavitation Erosion

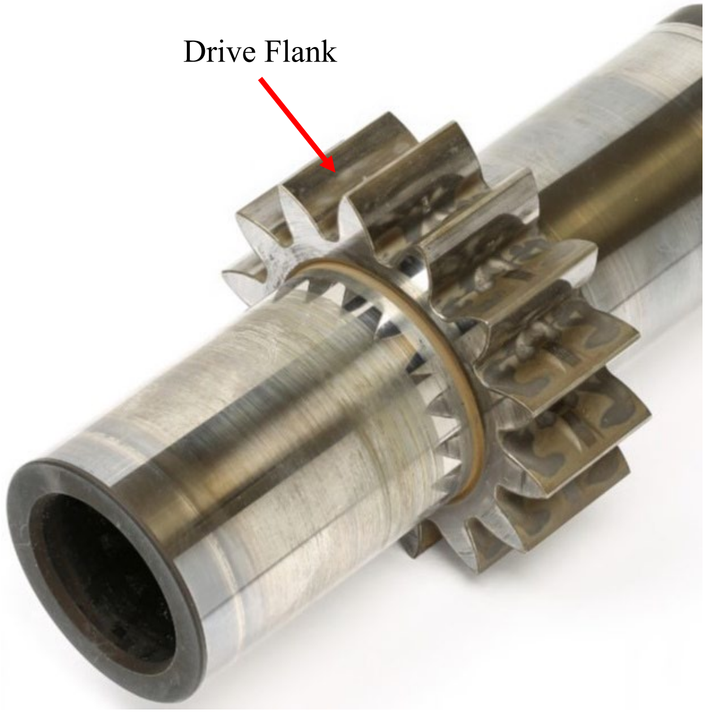


Photo 40 – Detail of HP Fuel Pump Drive Gear Tooth

Photo 41 – Section Through Cavitation in Drive Gear Tooth